ELECTRICAL ENGINEERING

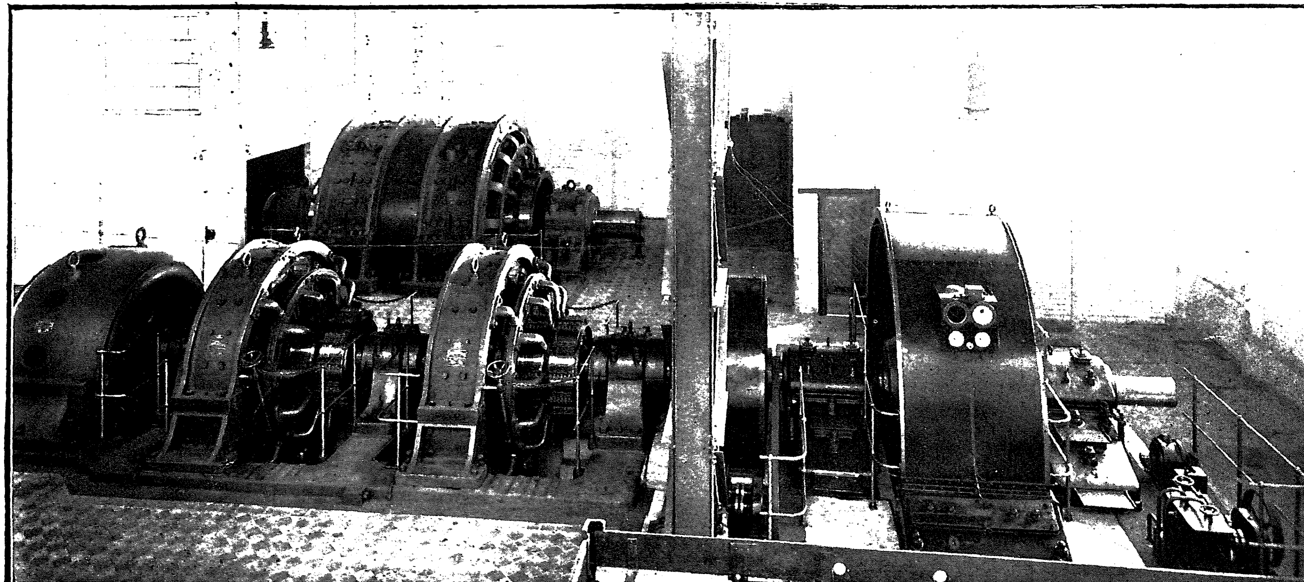
BY

T. C. BAILLIE, M.A., D.Sc., A.M.I.E.E.
Principal of the Croydon Polytechnics

VOL. I

INTRODUCTORY

Cambridge:
at the University Press
1915



English Electric Co., Ltd.

12 000 H.P. DIRECT-CURRENT REVERSING MILL MOTOR AND FLYWHEEL MOTOR-GENERATOR SET.

The main motor, in the background, is direct-coupled to a 36-in. reversing rolling mill. It is a double-armature machine with a speed range from 0 to 120 r.p.m. in both directions. Each armature is wound for 500 V, 8 400 A maximum current, and the two are connected in series. The machine weighs 194 tons and has a maximum shaft diameter of 30 ins. The motor generator set comprises a 3 ph., 2 650 V, 2 300 H.P. slip ring induction motor driving two variable-voltage D.C. generators, each capable of giving 8 400 A at 0 to 540 V (*see* Chapter 30, Volume II). These generators are connected in series or parallel by an electrically-operated switch. The flywheel, under the guard at the right, weighs 46 tons and stores 178 000 H.P.-seconds at 475 r.p.m.

[*Frontispiece*

ELECTRICAL ENGINEERING PRACTICE

A PRACTICAL TREATISE
FOR ELECTRICAL, CIVIL, AND MECHANICAL ENGINEERS

WITH

MANY TABLES AND ILLUSTRATIONS

BY

J. W. MEARES, C.I.E., F.R.A.S.
M.INST.C.E., M.I.E.E., M.I.E. (IND.)
ELECTRICAL ADVISER TO THE GOVERNMENT OF INDIA
LATE CHIEF ENGINEER, HYDRO-ELECTRIC SURVEY OF INDIA

AND

R. E. NEALE, B.Sc. HONS. (LOND.)
A.C.G.I., A.M.I.E.E.
DAVID SALOMONS SCHOLAR, SIEMENS MEDALLIST

FOURTH EDITION RE-WRITTEN AND ENLARGED

IN TWO VOLUMES
VOL. I

LONDON
CHAPMAN & HALL, LTD.
11 HENRIETTA ST., W.C. 2
1923

PREFACE.

Electrical Engineering Practice, like good wine, needs no bush; for it has arrived at the dignity of a Fourth Edition in a period of eight years. In the present edition a great deal of new matter has been added and the book has been entirely re-arranged to suit its broadened scope. For obvious reasons the work is now issued in two volumes, and the division of subject-matter between them is such as will meet the convenience of readers.

In this volume, Part I deals with definitions, materials, and measurements, embodying much information not included in the earlier editions. The generation and sale of electrical energy are treated in Part II. Care has been devoted to bringing these chapters into conformity with recent developments in the policy and practice of electricity supply in this country. The authors' experience indicates that the notes on power factor, load factor, and diversity factor, and the chapters on power-house development and on water-power will be appreciated widely.

Part III, on Transmission and Control, embodies new chapters on Switchgear and on the Protection of Machines and Circuits against abnormal conditions. It is believed that these will be found a valuable addition.

Volume II, now in preparation, deals with transformation, conversion, and storage; distribution and control in branch circuits; applications of electrical energy; and specifications, testing, rules and regulations. A considerable amount of fresh matter is being incorporated in this volume also.

Throughout the work the authors' aim has been to give that information, and that alone, which will be found useful in practice. Wherever a statement capable of practical exemplification is made, the example follows hot-foot. The original author has so frequently found statements in technical books, apparently clear but actually susceptible of more than one interpretation; where an example is given no ambiguity is possible.

PREFACE

Many valuable criticisms of the Third Edition were made in the course of the most favourable reviews that appeared in the technical press. It is confidently believed that the utility of the work to engineers generally, as well as to Electrical Engineers, has been enlarged by the present revision.

J. W. MEARES.
R. E. NEALE.

31*st July*, 1923.

EXTRACT FROM PREFACE TO THIRD EDITION.

(*N.B.*—In reprinting this Preface, those portions which are not in any way applicable to the present edition have been omitted.)

GREATLY daring, an endeavour has been made to fill the gap between the many excellent pocket-books of bare data and the highly technical works written for specialists in various branches of electrical engineering. The demand for the first two editions proves that this endeavour was successful so far as India was concerned, and no pains have been spared to make the present edition equally useful to engineers and students in this country. It is believed that the book will appeal to civil, mechanical, and electrical engineers alike; and though the whole field covered cannot be dealt with exhaustively in a single volume, the treatment presented should give the information and guidance meeting the needs of a very wide circle of readers.

Some of the matter presented is quite elementary and, from experience with the previous editions, by no means unnecessary or unappreciated. Even the hydraulic analogy has not been allowed to rest in the place to which it has so often been consigned. One point, in particular, which it helps to bring home to the first-year student is that we use as one of our chief electrical units a *rate*, the ampere, instead of the corresponding *quantity*, the coulomb. The irrigation engineer in India has coined the word 'cusec' (1 cubic foot per second) to express a *unit rate of flow* of water, which is exactly analogous to the ampere. Coulombs are seldom mentioned in practical electrical engineering, and the average engineer undoubtedly regards the coulomb in a roundabout way as an ampere-second—a multiple of a rate by a time—instead of as a definite quantity in itself. Even where ampere-hours are mentioned the electrical engineer often forgets that this larger unit of quantity would be one of the primary units in other branches of engineering, equivalent (say) to a gallon of water. Conceptions such as a yard or a gallon offer no difficulty to any intelligent being, but every one must have met with persons completely lacking in the geometrical sense, to whom an angle meant absolutely nothing. Further up the scale difficulty is experienced in explaining such compound terms as 'pounds-feet' or 'feet per second per second,' and

EXTRACT FROM PREFACE TO THIRD EDITION

when we arrive at the maximum demand system of charging for electrical energy, the average man frankly gives up attempting to grasp its significance. If, then, the explanations in this book appear at times too elementary, it is a lapse in the right direction.

It has been the author's aim to be severely practical; hence many terms used in electrical literature find no place in this volume, either because the reader will not need them in his daily work or, in so far as they deal with the elements of electricity and magnetism, because they are assumed to be already known to him. Where a term is used which has not so far been defined, the explanation will be found on a later page, and, in the absence of a forward reference, the index will guide the reader. Where definitions of terms are given, they are complete and for the most part accepted internationally; but it does not follow that they are self-explanatory in every case.

Practical examples have been used freely for the purpose of illustration, no amount of mere description being so effective in explaining rules and formulæ. For the same reason, diagrams of strictly utilitarian nature have been used to show plainly the connections and so forth described in the text. The examples chosen all make use of British standard frequencies, pressures, etc., and numerical results are those obtained by using the slide rule and omitting unnecessary figures. It is still often overlooked that the accuracy of any result is limited by that of the measurements and data which yield it; and that, whereas half a dozen significant figures may be accurate and necessary in scientific work, an accuracy to within even 1 per cent. is only accidental where commercial calculations or measurements with commercial instruments are concerned.

The lists of contents, tables, and illustrations will give a general idea of the scope and limitations of the book, and the index will guide the reader who uses the volume merely as a book of reference. Pains have been taken to make the index as complete as possible, and it should be noted that cross references and index references are to paragraphs, and that *paragraph numbers are shown at the head of pages* and page numbers at the foot. The symbols which have been accepted internationally to represent electrical quantities are used throughout this edition; their convenience and space-saving qualities are obvious, and it is curious that they have not yet come into general use.

J. W. MEARES.

LONDON, 21*st September*, 1916.

CONTENTS.

FOR CONTENTS OF VOLUME II. SEE P. 562.

CONTENTS

ELECTRICAL ENGINEERING PRACTICE

PART I.—DEFINITIONS: MATERIALS: MEASUREMENTS.

CHAPTER 1.

EXPLANATION OF ELECTRO-TECHNICAL TERMS.

UNITS AND DEFINITIONS.

(NOTE.—*A list of the Symbols and Abbreviations used throughout this book will be found in* §§ 6 *and* 7.)

1. Units.—As in most other branches of science, there are two systems of units for the measurement of electrical quantities, *viz. absolute units* and *practical units*. Absolute units are physical constants which are easily defined, but the measurement and actual reproduction of these units are difficult, and the units themselves are not of convenient magnitude for practical purposes. To overcome this objection, practical units have been adopted which are convenient multiples or sub-multiples of the corresponding absolute units. The accurate measurement and reproduction of practical units on this basis alone offer the same difficulties as in the case of the absolute units themselves, but special apparatus are installed in the various standardisation laboratories of the world to make possible comparisons between absolute standards and practical standards, the latter being constructed or established by international agreement. The instructions for materialising practical units are subject to periodical revision as the technology of precision measurements is improved.

2. Absolute Units.—Though absolute units are seldom employed in practical work (§ 1), it is desirable that the practical engineer should be familiar with the definitions and magnitudes of these units. Short definitions of the absolute units and values of the practical units in terms of the absolute units are given in Table 1.

TABLE 1.—*Absolute and Practical Units.*

Quantity.	Definition of Absolute Unit.	Practical Unit.	
		Name.	In Terms of the Absolute Unit.
Force.	*Unit Force* (1 *dyne*), acting on a mass * of 1 gramme for 1 second, imparts to it a velocity of 1 cm. per sec.	Gramme-weight	= 981 dynes.
	In foot-pound-second units, the unit of force is the *poundal* which, acting on a mass * of 1 pound for 1 second, imparts to it a velocity of 1 ft. per sec.	Pound-weight	= 32·2 poundals.
Work (energy).	*C.G.S. Unit Work* (1 *erg*) is done by a force of 1 dyne moving its point of application through a distance of 1 cm.	Foot-poundal Foot-pound Gramme-centimetre Joule Kilowatt-hour	= 421 390 ergs. = 13 568 760 ergs. = 981 ergs. = 10^7 ergs. = $3{\cdot}6 \times 10^{13}$ ergs.
Power.	*C.G.S. Unit Power* is that power which is capable of performing 1 erg per sec.	Watt	= 10^7 ergs per sec.
Unit pole or charge.	*Unit Magnetic Pole or Electrical Charge*, when distant 1 cm. in air from a like and equal pole or charge, repels (and is repelled) with a force of 1 dyne.	—	—
Magnetic field.	*A Magnetic Field of Unit Strength* exerts a force of 1 dyne on a unit pole placed at the point considered. (NOTE.—This field is arbitrarily represented by 1 line per sq. cm.)	Gauss	= 1 line per sq. cm. = flux density of field of unit strength.
Quantity of electricity.	*C.G.S. Electrostatic Unit Quantity* when distant 1 cm. in air from an equal quantity of like polarity, repels it with a force of 1 dyne.	Coulomb (1 ampere-second)	= 3×10^9 C.G.S. electrostatic units.
	C.G.S. Electromagnetic Unit Quantity is conveyed by 1 C.G.S. electromagnetic unit of current flowing for 1 sec.	Coulomb (1 ampere-second)	= $\frac{1}{10}$ × C.G.S. electromagnetic unit.
Current.	*C.G.S. Electrostatic Unit Current* is the current corresponding to the flow of 1 C.G.S. electrostatic unit of quantity in 1 sec.	Ampere	= 3×10^9 C.G.S. electrostatic units.

* The distinction between *mass* and *weight* is important. The mass, m, of a weight, w, is given by: $m = W/g$, where $g = 32{\cdot}2$ ft. per sec. per sec. = 981 cm. per sec. per sec.

TABLE 1 (*continued*).

Quantity.	Definition of Absolute Unit.	Practical Unit.	
		Name.	In Terms of the Absolute Unit.
Current.	*C.G.S. Electromagnetic Unit Current* in a wire 1 cm. long bent into an arc of 1 cm. radius exerts a force of 1 dyne on unit pole placed at the centre.	Ampere	$= \frac{1}{10} \times$ C.G.S. electromagnetic unit.
Potential.	A point is at *C.G.S. Electrostatic Unit Potential* if the work done on or by positive unit charge in moving from infinity to the point is 1 erg.	Volt	$= \frac{1}{300} \times$ C.G.S. electrostatic unit.
	There is *C.G.S. Electromagnetic Unit Difference of Potential* between two points if the work done in transferring C.G.S. electromagnetic unit quantity from one point to the other is 1 erg.	Volt	$= 10^8 \times$ C.G.S. electromagnetic units.
Resistance.	*C.G.S. Electromagnetic Unit Resistance* is the resistance of a conductor in which C.G.S. electromagnetic unit current is produced by C.G.S. electromagnetic unit potential difference between the ends of the conductor.	Ohm	$= 10^9 \times$ C.G.S. electromagnetic unit. $= [1/(9 \times 10^{11})] \times$ C.G.S. electrostatic unit.
Capacity.	*C.G.S. Electrostatic* (*Electromagnetic*) *Unit Capacity* is brought to a potential difference of 1 C.G.S. electrostatic (electromagnetic) unit by the application of C.G.S. electrostatic (electromagnetic) unit quantity of electricity.	Microfarad * (10^{-6} farad)	$= 9 \times 10^5$ C.G.S. electrostatic units. $= 10^{-15} \times$ C.G.S. electromagnetic unit.
Self (or mutual) inductance.	The coefficient of self-induction of a circuit is the number of lines of force linked with the circuit when the latter carries C.G.S. electromagnetic unit current. Two circuits have C.G.S. electromagnetic unit coefficient of mutual inductance when unit current passed through one circuit produces in the other a quantity of current = 1/R C.G.S. electromagnetic units of quantity; (R being the resistance of the second coil in electromagnetic units).	Henry	$= 10^9 \times$ C.G.S. electromagnetic unit.

* 1 electrostatic unit or centimetre = 1·11 micro-microfarad, and is a convenient unit for very small capacities such as are used in wireless telegraphy.

It will be seen that there are two systems of absolute units, *viz.* the C.G.S. (centimetre-gramme-second) electrostatic units and the C.G.S. electromagnetic units. The relations between the units in each of these systems are the same, but the actual dimensions of the electrostatic and electromagnetic units are not the same. This is because specific inductive capacity (§ 46) is taken as a numeral in the electrostatic system of units, whilst permeability (§ 43) is taken as a numeral in the electromagnetic system of units. There is a definite ratio between corresponding electrostatic and electromagnetic units, 1 C.G.S. electrostatic unit of potential being equal to 3×10^{10} C.G.S. electromagnetic units. The factor 3×10^{10} is the velocity of light, in cm. per sec. The electromagnetic unit of quantity is larger than the electrostatic unit in the ratio $3 \times 10^{10} : 1$, hence the electromagnetic unit of capacity (*see* definition in Table 1) is $(3 \times 10^{10})^2$ or 9×10^{20} times as great as the electrostatic unit.

The C.G.S. electromagnetic absolute units are the ones to which the units of the practical electrical engineer are generally referred.

3. International Definitions.—The international definitions of the practical electrical units, viz. resistance, R, the ohm; electromotive force or pressure, E, the volt; and current, I, the ampere, were adopted at a conference held in London in 1908, and were legalised by Order in Council in 1910. The explanatory notes that follow will make clearer the definitions of these quantities and their derivatives. The preliminary explanations are by no means exhaustive, and most of the matters dealt with will be treated more fully in subsequent chapters, as occasion arises. The actual definitions do not greatly concern the average engineer, but they may be set forth for completeness.

The International Ohm (Ω) is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice 14·452 1 grammes in mass of a constant cross-sectional area and of a length of 106·300 centimetres.

Note.—The use of Ω as the symbol for megohm is no longer permissible; *see* footnote to Table 3, § 6.

The International Ampere (A) is the unvarying electric current which when passed through a solution of nitrate of silver in water deposits silver at the rate of 0·001 118 00 of a gramme per second.

The International Volt (V) is the electrical pressure which when steadily applied to a conductor whose resistance is one International Ohm will produce a current of one International Ampere.

These definitions are further expanded in the Order in Council, where the particular standards and methods of determination are set forth.* To these may be added also the accepted definition of the unit of power, the watt (W).

The Watt is the unit of power, and is the energy expended per second by an unvarying electric current of one ampere under an electrical pressure of one volt.

---

* *The Law Relating to Electricity*, by C. M. Knowles, part i, p. 417.

4. Definitions from the Wiring Rules of the Institution of Electrical Engineers.—In the course of this work, especially in the chapters on installing wiring in buildings, reference will frequently be made to the I.E.E. Wiring Rules.

The Rules embody the requirements and precautions which the Institution of Electrical Engineers has framed to secure satisfactory results with a supply of electrical energy at low pressures, not exceeding 250 V, and also, with such additional requirements as are indicated herein, for medium pressures exceeding 250 V but not exceeding 650 V. They include only such requirements and precautions as are necessary under ordinary conditions, and they are not intended either to take the place of a detailed specification, or to instruct untrained persons.

The rules contain a number of generally accepted definitions of electrical terms and apparatus, with which these pages deal, and a list of these will be found useful.

System means an electrical system in which all the conductors and apparatus are electrically connected to a common source of supply. (Chapter 20.)

Three-wire System.—A three-wire system is one in which three conductors are maintained at different potentials, the neutral conductor at a potential intermediate between the highest and lowest being common to all lamps or other consuming devices supplied on either side of the system. (Chapter 20.)

Outer Conductors.—Those between which there is the greatest difference of potential. This use of the word *outer* must not be confused with the use of the word when applied to the external conductor of a concentric main.

Neutral Conductor.—That which is at a potential intermediate between the potentials of the other conductors. (Chapter 20.)

Earthed.—Connected to the general mass of the earth in such a manner as will ensure at all times an immediate and safe discharge of electrical energy. (Chapter 20.)

Dielectric.—Any material which offers high resistance to the passage of an electric current (§ 280).

Uninsulated Conductor.—A conductor without provision, by the interposition of a dielectric or otherwise, for its insulation from earth.

Bare.—Not covered with insulating material.

Bunched Conductors.—When more than one conductor is contained within a single duct or groove, or when they are run unenclosed and not spaced apart from each other. (Chapter 23.)

Fuse-switch.—A quick-break switch with fuse forming an integral part of the switch.

Point.—In wiring. The termination of the wiring for attachment to the fitting for one or more lamps or other consuming devices.

Single-pole Switch.—A switch controlling one conductor only of a circuit.

Linked Switches.—Switches linked together mechanically so as to operate simultaneously, or in definite sequence.

Switchboard.—An assemblage of switches, fuses, conductors, measuring instruments, and other apparatus for the control of electrical machinery and circuits.

Grade of Insulation 250 V *Cable.*—Vulcanised rubber cable is said to be I.E.E. 250 V cable when the minimum radial thickness of its dielectric is that shown in

col. 9 of the table,* and when its minimum insulation resistance is that shown in col. 5 after application of a pressure test of 1 000 V for half an hour.†

Grade of Insulation 650 V *Cable.*—Vulcanised rubber cable is said to be I.E.E. 650 V cable when the minimum radial thickness of its dielectric is that shown in col. 10 of the table,* and when its minimum insulation resistance is that shown in col. 6 after application of a pressure test of 2 500 V for half an hour.†

Protected Machine.—One having end shield bearings, and in which there is free access to the interior without opening doors or removing covers.

Semi-enclosed Machine.—One in which the ventilating openings in the frame are covered with: (*a*) grids, expanded metal or wire gauze, with openings of not less than $\frac{1}{4}$ in., so as not to obstruct free ventilation; (*b*) wire gauze, in which the openings are less than $\frac{1}{4}$ in. but not less than $\frac{3}{32}$ in., or with perforated metal having holes not less than $\frac{3}{16}$ in. (diameter or width); (*c*) screens with smaller openings than the above.

Totally Enclosed Machine.—One in which the enclosing case and bearings are dust-proof, and which does not allow circulation of air between the inside and outside of the case.

Pipe-ventilated Machine.—An enclosed machine in which the frame is so arranged that the ventilating air may be conveyed to it through a pipe attached to the frame, the ventilation being maintained by the fanning action produced by the machine itself.

Forced-draught Machine.—An enclosed machine in which the ventilating air-supply is maintained by an independent fan external to the machine itself.

Many of the foregoing definitions will be expanded and further explained in the following chapters.

5. Definitions in Regulations and Standard Reports.—In official regulations, such as those relating to the use of electricity in factories, workshops, and mines (Chap. 41), and in standardisation reports such as those issued by the British Engineering Standards Association (*ibid.*), special definitions are given of the meanings to be attached to certain terms for the purposes of the regulations, etc. Some of these definitions differ from the meanings commonly attached to the terms in question, and it is important that the official interpretations should be studied carefully.

SYMBOLS, SIGNS, ETC.

6. Abbreviations and Symbols.—Except where otherwise stated, the symbols recommended by the International Electrotechnical Commission are used throughout this book. Though all the symbols are not here required the list is reproduced in full, save for the omission of alternative symbols which are recom-

* *See* Table 40, § 280.

† The pressure test and insulation resistance test must be applied as specified in Rules 47 and 48 (§ 280).

mended by the Commission for cases in which the principal letter symbol is not suitable.*

A list of letter symbols most frequently needed in electrotechnics is given in Table 2. Abbreviations for names of units are given in Table 3.

Rules for Quantities.—(*a*) Instantaneous values of electrical quantities which vary with the time to be represented by small letters. In case of ambiguity, they may be followed by the subscript 't.'

(*b*) Virtual or constant values of electrical quantities to be represented by capital letters.

(*c*) Maximum values of periodic electrical and magnetic quantities to be represented by capital letters followed by the subscript 'm.'

(*d*) In cases where it is desirable to distinguish between magnetic and electric quantities, constant or variable, magnetic quantities to be represented by capital letters of either script, heavy-faced or any special type. Script letters to be only employed for magnetic quantities.

(*e*) Angles to be represented by small Greek letters.

(*f*) Dimensionless and specific quantities to be represented, wherever possible, by small Greek letters.

TABLE 2.—*Letter Symbols Most Frequently Needed in Electro-technics.*

Name of Quantity.	Letter Symbol.	Name of Quantity.	Letter Symbol.
Length	l	Resistivity	ρ
Mass	m	Conductance	G
Time	t	Quantity of electricity	Q
Angles	α, β, γ	Flux-density, electrostatic	D
Acceleration of gravity	g	Capacity	C
Work	A	Dielectric constant	ϵ
Energy	W	Self-inductance	L
Power	P	Mutual inductance	M
Efficiency	η	Reactance	X
Number of turns in unit of time	n	Impedance	Z
Temperature centigrade	t	Reluctance	S
Temperature absolute	T	Magnetic flux	Φ
Period	T	Flux density, magnetic	B
$2\pi/T(=2\pi f)$	ω	Magnetic field	H
Frequency	f	Intensity of magnetisation	J
Phase displacement	ϕ	Permeability	μ
Electromotive force	E	Susceptibility	κ
Current	I	Difference of potential, electric	V
Resistance	R	Magnetomotive force	†

* The complete Report (No. 27) may be purchased from the International Electro-technical Commission at 28 Victoria Street, Westminster, S.W. 1.

† Symbol to be proposed by the National Committee.

TABLE 3.—*Abbreviations for Names of Units; to be used only after Numerical Values.*

Name of Unit.	Abbreviation.*	Name of Unit.	Abbreviation.*
Ampere	A	Volt-coulomb	VC
Volt	V	Watt-hour	Wh
Ohm	Ω †	Volt-ampere	VA
Coulomb	C	Ampere-hour	Ah
Joule	J	Milliampere	mA
Watt	W	Kilowatt	kW
Farad	F	Kilovolt-ampere	kVA
Henry	H	Kilowatt-hour	kWh

m for milli- μ for micro- or micr-
k for kilo- M for mega- or meg-

Other abbreviations used in this book are as follows :—

Inch	in.	Power factor	P.F. or cos ϕ.
$\frac{1}{1000}$ inch	mil.		
Foot	ft.	British Thermal Unit	B.Th.U.
Yard	yd.	Board of Trade Unit	
Mile	ml.	(or Kelvin)	B.T.U. or unit.
Metre	m.	Standard wire-gauge	S.W.G.
Kilometre	km.	Home Office	H.O.
Centimetre	cm.	Board of Trade	B.O.T.
Millimetre	mm.	International Electro-	
Square	sq.	technical Commis-	
Cubic	cu.	sion	I.E.C.
Gramme	grm.	British Engineering	
Kilogramme	kg.	Standards Associa-	
Continuous or direct		tion	B.E.S.A.
current	C.C. or D.C.	Institution of Elec-	
Alternating current	A.C.	trical Engineers	I.E.E.
Positive pole	+	British Electrical and	
Negative pole	−	Allied Manufactur-	
Neutral, D.C.	±	ers' Association	B.E.A.M.A.
Neutral, A.C.	N.	British Electrical and	
Earth	E.	Allied Industries	
Horse-power (indi-		Research Associa-	
cated or brake)	I.H.P.; B.H.P.	tion	B.E.R.A.
Electrical horse-power	E.H.P.		

7. **Conventional Signs for Electrical Diagrams.**—A number of conventional signs for electrical apparatus are given in Table 4. About 750 symbols are given in the British Engineering

* The I.E.C. recommends that these abbreviations should be in heavy-faced type, but for economy in printing, and following the practice adopted in the *I.E.E. Journal* and in the technical press, ordinary type is used for these abbreviations throughout this book.

† The letters O and Ω are recommended provisionally. Ω is used in this book because O is liable to be confused with the numeral zero. The letter Ω should no longer be used for megohm.

Standards Association's Report (No. 108/1922) on British Standard Graphical Symbols for Electrical Purposes. The symbols in Table 4 are consistent with the Standard Symbols, and are used in most diagrams in this book except where other methods of representation are more convenient for purposes of explanation. The main utility of the Standard Symbols is in the preparation of plans and connection diagrams for commercial purposes, and it is most desirable that they should be used in all such work.

Notes.—(*a*) Conductors are represented by lines, the thickness of which may often be varied to discriminate between main (heavy current) circuits and instrument (or other weak current) circuits. Diagrams may frequently be simplified with advantage by using single lines to represent *circuits* (lead and return), the number of wires in the circuit being then denoted by an equal number of *diagonal* strokes across the circuit-line (*see* (4), Table 4). Strokes at *right angles* to the circuit-line are taken to represent that number of complete circuits connected in parallel (*see* (5) Table 4).

(*b*) Connections between conductors should be represented by a dot at the junction. Lines crossing without a dot are often used to represent conductors which cross without connection between them, but the authors prefer the method of indicating this definitely by a semicircle in one conductor at the point of crossing.

(*c*) Single-phase, two-phase, and three-phase alternating currents are frequently represented in diagrams by 1 ~, 2 ~, and 3 ~ respectively. The only objection to this is that ~ is even more commonly used to represent the frequency in cycles per sec., thus 50 ~, 100 ~, etc. The risk of confusion is slight because frequencies of 1, 2, and 3 cycles per sec. are never used for commercial purposes. There are, however, 'slip' currents of very low frequencies in some A.C. motors (*see* Chapter 28) so that to avoid possibility of confusion it seems best to use the symbols 1ϕ, 2ϕ, and 3ϕ where a graphical representation is required for single-, two-, and three-phase currents.

(*d*) Instruments may be represented by a circle, or by an outline of the shape of the instrument, within which is a letter symbol indicating the purpose of the instrument. Relays may be represented by a rectangular outline containing appropriate letter symbols. Symbol letters for instruments and relays were standardised by the B.E.A.M.A. in their Standardisation Rules for Electrical Machinery, and these conventions, with minor modifications, have now been standardised by the B.E.S.A. as follows:—

Ammeter, indicating	A.	Frequency meter	F.
Ammeter, recording	RA.	Synchroscope	S.
Voltmeter, indicating	V.	Galvanometer	Gal.
Voltmeter, recording	RV.	Overload relay, constant time limit	OR/CT.
Wattmeter, indicating	W.		
Wattmeter, recording	RW.	Overload relay, inverse time limit	OR/IT.
Ampere-hour meter	AH.		
Watt-hour meter	WH.	Reverse current relay	R/CR.
Power factor meter	PF.	Reverse power relay	R/PR.

(*e*) In the conventional sign for a primary cell (*see* No. 38, Table 4), the thick stroke should represent the *electro-positive element of the cell* (*e.g.* the zinc in a

TABLE 4.—*Conventional Signs for Electrical Diagrams.*

No.		Conventional Sign.
1	Conductors (*a*) Main. (*b*) Small.	(*a*) (*b*)
2	Conductors (*a*) Connected. (*b*) Crossing.	*a* *a* *b* or *a* *a* *b*
3	Twin flexible conductors.	
4	Two (*a*) and three (*b*) wire *circuits* (lead and return).	(*a*) (*b*)
5	Two (*a*) and three (*b*) *circuits* in parallel.	(*a*) (*b*)
6	Bus bar.	
7	Bus bar with terminals.	
8	Link.	
9	Cut-out.	
10	Earth connection (*a*), and plate (*b*).	(*a*) E (*b*)
11	Generating station (*a*) Thermal (*b*) Hydraulic	(*a*) (*b*)
12	Sub-station.*	
13	Direct current (*a*) Generator. (*b*) Motor.	G or (*a*) G; M or (*b*) M
14	Single-phase (*a*) Generator. (*b*) Motor (i) synchronous. (ii) asynchronous.	(*a*) G See Note (*c*); M (i) (*b*) M (ii)
15	Two-phase, 3-wire: (*a*) Generator; (*b*) Motor.	G (*a*) M (*b*)
16	Two-phase, 4-wire: (*a*) Generator; (*b*) Motor.	G (*a*) M (*b*)
17	Three-phase (*a*) Generator. (*b*) Motor (i) synchronous. (ii) asynchronous.	(*a*) G 3~ See Note (*c*); M 3~ (i) (*b*) M 3~ (ii)
18	Three - phase generator: (*a*) Mesh; (*b*) Star.	(*a*) (*b*)
19	Rotary converter.	
20	Motor-generator.	M-G
21	Motor-converter.	M-C
22	Mechanically - coupled machines (motor and generator in the case shown).	M G
23	Non-inductive resistance.‡	or
24	Inductive winding (field coil, etc.)	
25	Commutating-pole winding.	
26	Transformer.	or
27	Socket for plug.	
28	Plug and socket.	
29	Tumbler switch (*a*) Single-pole. (*b*) Double-pole.	(*a*) (*b*)
30	Rotating switch, single-pole.	
31	Single-pole switch: (*a*) Air break; (*b*) Oil-immersed.	(*a*) (*b*)
32	Air-break circuit breaker (maximum trip).	
33	Contactor.	b
34	Instruments and relays.	See Note (*d*)
35	Incandescent (glow) lamp.	or or L
36	Arc lamp.	
37	Fan.	
38	Battery of cells.§	+ –

N.B.—For notes (*a*)-(*e*) see § 7; for footnotes see opposite page.

primary battery or the spongy lead in an accumulator) which is the *negative pole* of the battery and the thin stroke the electro-negative element which is the positive pole. There is much confusion over this matter. Inside a cell the current travels from the electro-positive to the electro-negative element; from the zinc to the carbon; from the lead to the lead peroxide; so in the external circuit these directions are necessarily reversed. The arrows in diagram 38, Table 4, show this.

Some further conventional signs used in connection with wiring diagrams for lighting installations, are given in Chapter 22.

ELEMENTARY CONCEPTIONS.

8. Elementary Conception of Electrical Quantities.—The analogy between hydraulics and electricity is not in great favour amongst electrical engineers, but it is nevertheless very useful —so far as it goes—in explaining elementary electrical ideas. Voltage in an electric circuit is analogous to water pressure in an hydraulic system, and the rate of flow of electricity, measured in amperes, corresponds to the rate of flow of water. Though there is no actual identity, volts may be likened to lbs. per sq. in., and amperes may be likened to gallons per min. or cusecs.

Take, for example, the case of the pressure pipe in a water turbine installation. The power available at the nozzle in foot-pounds of energy per sec. (550 ft.-lbs. per sec. = 1 H.P.) is the product of the quantity of water flowing per sec. (*i.e.* the rate of flow) and the net head or pressure. We have a pipe of a certain size, with a certain weight of water flowing through it per sec. under a certain net head, which is the gross head diminished by the loss in frictional resistance in the pipe; the larger the diameter of the pipe, the smaller is this resistance loss. Similarly, in an electrical circuit, the power available in watts (100 W = 0·134 H.P. = 74 ft.-lbs. per sec.) is the product of the current or rate of flow in amperes, I, and the pressure in volts, E. Here, in the place of the pipe, we have a conductor of a certain size, and the pressure available for doing work is the initial pressure diminished by the loss due to the resistance, R, of the conductor to the flow of the current; and the larger the diameter of the conductor the smaller is the loss of pressure.

---

* In B.E.S.A. Report, No. 108, there are given various graphical symbols for insertion in the square frame representing a sub-station, to denote the equipment installed.

‡ Where it is necessary to discriminate, the triangular zig-zag should be used for resistances which are nearly non-inductive, and the rectangular zig-zag for those which are absolutely non-inductive.

§ The dotted line outside the battery is *not* part of the conventional sign but is added for the purpose of the explanation given in Note (*e*).

9. **Elementary Conception of a Circuit.**—This analogy, however, fails to explain the idea of an electric circuit (Chapter 19), and for this purpose the circulation in an ordinary hot-water installation may be cited. From the top of the boiler, as is well known, a pipe rises to the highest point in the system, and a current flows up this pipe. The fire supplies the motive force, which may be likened to the electromotive force of an electric battery or generator, and the hot-water pipe is the out-going conductor or 'lead.' But no circulation of water can take place unless there is a return circuit back to the boiler, and for this purpose a return pipe comes down from the top of the building to the lower part of the boiler. This pipe corresponds to the 'return' wire of an electric circuit. Whereas the closing of a valve on the water pipe breaks the circuit and stops the current, so the opening of a switch connected in the electrical conductor opens or breaks the circuit and stops the electric current. There is a difference, however, in that the temperature of, and total heat in, the water stored in the tank at the top increase when no supply is being drawn off, and the circulation continues all the time; but in an electrical circuit there is no such storage or circulation of energy when it is not being utilised. The lamps or other consuming devices bridge over and complete the circuit between the lead and return wires; and if the lamps are removed (or if the switch controlling them is opened, which comes to the same thing) then no current can flow. The electromotive force, or the difference of electric potential, between the two wires remains, but as there is no conducting circuit no current can flow. Here the analogy with a hot-water supply system holds good again; for, although the closing of a valve causes the circulation to cease, the pressure remains, and with it the tendency for the flow to restart as soon as it has a path open; and the same may be said in the case of the electric circuit. If the pressure is excessive it may in either case break down the opposing barrier, by bursting the pipe or valve in the one case and by sparking across the gap in the circuit in the other. A further interesting link in this analogy may be forged from the heat losses in the two circuits: the hot-water pipes are radiating energy away to the air, according to their temperature, and heat units supplied by the fuel are thus wasted; similarly the electrical conductors are raised in temperature by the current in them, and heat units supplied by the fuel are wasted in the form of I^2R watts (§§ 17, 49). A good grasp of this general idea of an electric

circuit will make it easier to understand the explanations which follow.

Kinds of Current.

10. **Alternating and Continuous Currents.**—The international definitions of the practical units of resistance, current, and pressure (§ 3) make specific mention of 'an unvarying electric current,' *i.e.* an electric current which is constant in magnitude and direction. Such a current may be produced by electrochemical action in a primary battery (§ 127), but the electric currents used for commercial purposes are induced in the windings of dynamo-electric machines by alternately increasing and decreasing the magnetic flux which passes through or is 'linked' with these windings. The process is described in detail in § 132, but for our present purpose it is sufficient to say that the periodic increase and decrease in the flux linked with the winding induces in the latter an electromotive force which varies periodically between positive and negative maxima. In other words, the electromotive force (and the current, if there is a closed circuit, § 9) alternates in direction and varies in magnitude. The currents induced in the windings of all dynamo-electric machines (excepting unipolar machines, § 137) are *alternating*, but the alternating electromotive forces and currents of the individual windings can be commutated or rectified (§§ 13, 132) and added together so as to produce a substantially unvarying electromotive force and current in the circuit supplied by the machine (§ 14).

So far as the internal arrangements in an installation are concerned, whether for lights, fans, or heating, etc., it generally makes no practical difference whether the supply is continuous or alternating current. If large motors or other inductive apparatus are involved the case is different; and where the design of machinery or the laying out of a large scheme is in question the essential differences in the systems must be properly understood.

11. **Single-Phase Alternating Current.**—When a coil of wire passes successively the two poles of a magnet, as in Fig. 1, so as to cut the lines of magnetic force at right angles, a wave of E.M.F. is generated, which rises to a positive maximum as one pole is passed, falls to zero, and then rises to a negative maximum as the other pole is passed, as shown by the full curve in Fig. 1.

The points A, B, C, D, on the pressure curve represent the E.M.F. induced in the coil when the latter is successively in the equidistant positions marked A, B, C, D, in the left-hand diagram. Assuming the ends of the coil to be joined, so as to make a circuit, this E.M.F. causes a corresponding cycle of waves of current to flow, and we have a simple 'single-phase' alternating current as represented in Fig. 1 by the dotted curve. The wave of E.M.F. and the consequent wave of current may or may not be coincident with respect to time, *i.e.* the maxima and minima may or may not occur simultaneously; in the figure the waves are shown as not coincident, *i.e.* they are somewhat 'out of phase.' Time and/or angle of rotation of the winding being plotted from left to right in Fig. 1, the dotted wave is behind, or 'lags' with regard to the full-line wave by a time interval t which is equivalent to

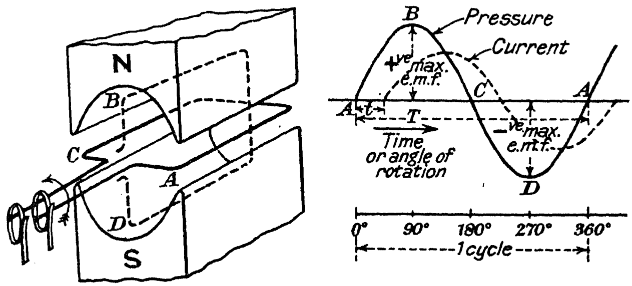


FIG. 1.—Alternating pressure and current.

$(t / T) \times 360°$, *i.e.* about 45° in the case illustrated. In some cases (*see also* §§ 46 and 47 and Chapter 5) the current wave is 'leading,' *i.e.* ahead of the pressure wave as regards relative position or 'phase.' The further explanation of this phenomenon, and of the peculiarities of alternating currents generally, is deferred to §§ 29-31, 44-47, 56; for the present it will be sufficient to assume that the current or pressure will be what is indicated in amperes or volts on a suitable measuring instrument.

Theoretically the wave is treated as a simple harmonic wave or 'sine wave.' By means of the oscillograph the exact shape of the wave form can be seen or photographically recorded, just as the inner working of the steam in an engine cylinder can be shown by an indicator diagram. In this way the irregularities from the true sine wave form can be examined, and in some cases they may be of considerable importance. As in an alternating current the

direction is reversed each half-cycle, alternating current cannot be used for electrochemical deposition or any work of that nature; for the work done in one half-cycle would be undone in the other half. A continuous current must be used in such cases, and its (conventional) direction must be correct when the circuit is made (§ 127). For electric lighting or heating or motive power either continuous or alternating current can be used. To obtain C.C. from an A.C. supply a motor-generator, converter, or rectifier must be used (Chapter 17).

12. Cycles or Periods.—The complete double wave of an alternating E.M.F. or current is called a 'cycle' or 'period,' and the number of periods per sec. is called the 'frequency' or 'periodicity.' The standard frequency of the British Engineering Standards Associations is 50 periods per sec. with 25 periods as a secondary standard to meet special cases. American practice favours 60 cycles per sec. as the standard (§ 135). For electric traction work, a frequency of 15 periods is often used; with this low frequency a glow-lamp actually shows the alternations, for as the wave of current dies down to zero the filament of the lamp cools down and the light diminishes. The result is a succession of flickers. On the other hand, it may be mentioned that frequencies of 10 000 alternations or more per sec. are used in wireless telegraphy.

13. Rectified Current.—If the arrangements are such that the waves below the zero line in Fig. 1 are reversed, we then have a unidirectional or rectified alternating current (*see* Chapter 17). The generator illustrated in Fig. 1, having only a single armature coil, would give such a current. Fig. 2 shows the form of the rectified wave. If there is a definite break between successive waves, this becomes an 'interrupted current' such as is found in an electric bell or an X-ray coil, whether worked by an ordinary 'make and break' magnet and spring or by a mechanical interrupter.

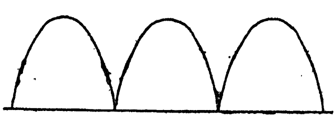


Fig. 2.—Rectified alternating current.

14. Continuous Current.—A very near approach to a steady unidirectional or 'continuous' current, such as is given by a battery, is generated by a dynamo, in which the waves of current generated by each coil successively are rectified by the commutator

and, rapidly succeeding one another, give almost a straight line on the crest of the resultant wave. This is shown developed gradually in Fig. 3. If the generator makes 15 or 20 revs. per sec. and the commutator has 60 or 80 sections, it is evident that there can be no appreciable fluctuation as the collecting brush passes from one section to the next.

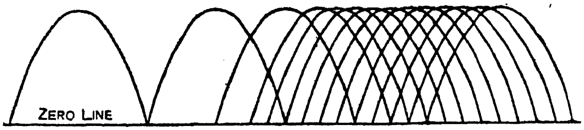


FIG. 3.—Continuous current.

15. **Three-Phase Current.**—For transmission of power over long distances '3-phase' alternating current is now almost universal. Referring back to Fig. 1, one complete cycle of pressure or current (corresponding in a two-pole machine, to one revolution, *i.e.* 360° rotation of the armature) may be represented as starting at zero, rising to a positive maximum at 90°, cutting the zero line again at 180,° rising to a negative maximum at 270°, and ending at 360°. In a 3-phase generator, there are three windings

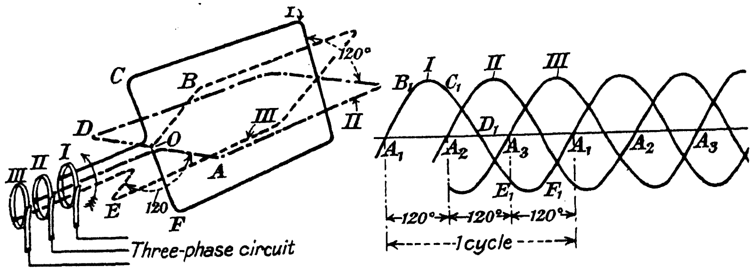


FIG. 4.—Three-phase current.

(represented by *I*, *II*, *III*, Fig. 4) spaced 120° apart. Thus, in addition to the pressure wave *I*, there is a second independent wave generated in the winding *II*, and a third wave generated in the winding *III*. The three waves are exactly similar, but are displaced 120° from each other. As shown in the diagram the three windings are 'star-connected' (§ 143) to a common neutral point O, but the action is just the same if each winding be led out to a separate pair of slip-rings. The use of six slip-rings and six wires in the external circuit is unnecessary because the algebraic sum of

the currents in any two phases of a 3-phase, 3-wire system is always equal and opposite to the current in the third phase, hence each pair of conductors can be considered to act as the return path for the current in the third conductor. There are, however, three separate and distinct waves of E.M.F., each producing a separate current when the circuit is closed. The 3-phase system makes possible the greatest practical economy in the transmission of power (*but see* § 298); it is explained further in Chapters 14 and 20.

16. Two-Phase Current.—It is only necessary to mention that 2-phase supply—with an angle of 90° between the phases—has been used considerably in the past; but the greater economy of 3-phase current has rendered this system almost obsolete. The 2-phase system is not dealt with in this book.

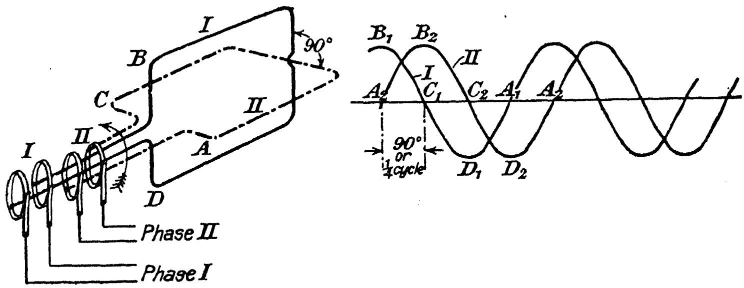


FIG. 5.—Two-phase current.

For the sake of completeness, Fig. 5 is included. This diagram is arranged similarly to Figs. 1 and 4, and is self-explanatory.

OHM'S LAW.

17. Ohm's Law.—The relation between resistance, R, pressure or electromotive force, E, and current or intensity of current, I, assuming all to be unvarying, is expressed by Ohm's Law as follows: The strength of the current varies directly as the electromotive force and inversely as the resistance of the circuit, or—

$$I = E / R, \text{ or } R = E / I, \text{ or } E = IR.$$

As mentioned already in § 8, the product of E and I expresses the power in the circuit in watts, W, which is directly comparable to, and convertible into, horse-power. By definition watts = EI. But $E = IR$. Therefore watts = I^2R (§§ 48-50). In succeeding

paragraphs examples will be given of the practical working of this rule; its application is not always so simple as may appear at first sight (§§ 21, 28, 44, 49, etc.).

Ohmic resistance does not alone determine the resistance to current flow in A.C. circuits, hence a modified form of Ohm's Law must be used for these circuits (§ 44).

RESISTANCE.

18. Resistivity and Conductance.—The resistivity or specific resistance of a material is the electrical resistance between opposite faces of a unit-cube of the material at specified temperature. Generally the specific resistance is expressed in microhms per centimetre-cube * (or per inch-cube) at 0° C. (§ 61), or in ohms per mil-foot., *i.e.* per foot of wire of 1 mil diameter. (1 Ω per mil-foot = 0·166 microhm per cm.-cube. 1 microhm per cm.-cube = 6·015 Ω per mil-foot).

The resistance between two opposite faces of a 1 cm.-cube of a material is termed the *volume resistivity* of the material. Denoting this by ρ_v Ω, the resistance R of a uniform wire of length l cm. and cross-section A sq. cm. is: $R = \rho_v l / A$ Ω. If the density of the material be D grm. / cu. cm., the mass m of the wire considered is: $m = lAD$ grm., hence $A = m / lD$. Substituting this value for A we have $R = \rho_v Dl^2 / m$. The product $\rho_v D$ does not vary with the dimensions of the wire, and is called the *mass resistivity* (ρ_m) of the material. The coefficients ρ_v, D, and ρ_m all vary with temperature.

It is usual to express ρ_v in microhms per cm.-cube. The resistance R Ω, of a uniform wire L metres long and of mass m grm. is then given by $R = \rho_m L^2 / m$; where $\rho_m = \rho_v D / 100$. Thus for copper $\rho_m = 0{\cdot}153\,28$ Ω at 20° C. (§ 62) and the resistance of a wire 5 metres long and of mass 50 grm. is $R = 0{\cdot}153 \times (5)^2 / 50 = 0{\cdot}076\,5$ Ω (approx.).

Conductance is the reciprocal of resistance, $1 / R$, and is expressed in 'mhos,' a coined word obtained by writing 'ohm' backwards. The use of this term is explained further in Chapter 19.

---

* It is essential to use the term centimetre-cube (or inch-cube) and *not* the term cubic centimetre (or cubic inch) in this connection. The resistance of 1 cm.-cube of copper is about 1·6 microhms at 0° C. The resistance of 1 cu. cm. of copper is 1·6 microhms if the metal is in the form of a 1 cm.-cube, but since the resistance of a conductor is directly proportional to its length and inversely proportional to its cross-sectional area, it is 1·6 × 100 × 100 = 16 000 microhms = 0·016 Ω if the 1 cu. cm. of metal is in the form of a wire 1 m. long and 1 sq. mm. cross-section.

19. Ohms, Megohms.—Resistance is expressed in 'ohms' in all ordinary cases, when dealing with conductors or conducting circuits. If, however, the resistance of a nominally insulating body is required a higher unit is desirable, and the result is expressed in 'megohms,' *i.e.* millions of ohms. Thus, in the case of insulated wires and cables, the covering or 'dielectric' of a particular quality will be guaranteed to have an 'insulation resistance' of not less than 300, 600, or 2 000 megohms per ml. at a certain temperature, as explained more particularly in § 281.

20. Standard Resistances.—For accurate electrical measurements by means of the potentiometer (§ 95) standard comparison coils of 1 Ω, and decimal multiples up to a megohm or submultiples down to 0·001 of an ohm, are used; for these the alloy manganin is generally employed, as its temperature coefficient is almost negligible. These are called 'standard resistances'; they are also used in some portable testing sets (*see* § 106). In order to reduce the amount of metal used in standard resistances for large currents they are frequently made tubular and water circulates through them.

21. Internal and External Resistance.—In a complete circuit, carrying a current from a battery or other source of power included in it, the total resistance is made up of the 'internal resistance' of the battery or generator and the 'external resistance' consisting of the remainder or working part of the circuit. This must not be overlooked in applying Ohm's Law. A battery (§ 127) of small cells may easily be connected in series so as to have a total pressure of 1 000 V on 'open circuit,' *i.e.* with no *external* connection from pole to pole; but if a conductor having a resistance of 1 Ω is connected across its terminals the current in the circuit will not be 1 000 A or perhaps not even 1 A; for to the external resistance of 1 Ω must be added the very high internal resistance of the whole of the cells. In this case $I = E / R$ may be written $I = E / (R + r)$, where R and r are the external and internal resistances respectively.

Pressure.

22. Definition of Pressure.—The term 'pressure' or electromotive force (E. or E.M.F.) is defined in more than one way in the regulations of the Board of Trade and the Home Office, but the variations are not material. The following is explicit:—

Pressure means the difference of electrical potential between any two conductors through which a supply of energy is given, or between any part of either conductor and the earth, as read by a hot-wire or electrostatic voltmeter.

Low Pressure means a pressure in a system normally not exceeding 250 V where the electrical energy is used.

Medium Pressure means a pressure in a system normally above 250 V, but not exceeding 650 V, where the electrical energy is used.

High Pressure means a pressure in a system normally above 650 V, but not exceeding 3 000 V, where the electrical energy is used or supplied.

Extra-high Pressure means a pressure in a system normally exceeding 3 000 V where the electrical energy is used or supplied.

The reference to *normal* pressure refers to the variations which are permitted by the regulations for public supply.

The phrase 'difference of potential' or 'potential difference' (P.D.), used in the above definition, is frequently used in discussing the electrical conditions in a circuit; the technical distinction between the two modes of expression will be grasped as the reader proceeds. The nature of alternating, as opposed to continuous current has already been discussed (§§ 11-16), and the meaning of the term 'pressure' as applied to an alternating current supply is further elucidated in §§ 29-31.

23. British Standard Pressures.—In Report No. 77, 1921, the British Engineering Standards Association specifies British standard electrical pressures for new systems and installations as follows:—

(a) *Direct Current Systems and Installations.*

(i) Consumer's pressures.*—220, 440 V.

(ii) Station pressures.†—242, 484 V.

(b) *Alternating Current* (*3-phase*) *Systems and Installations.*

(i) Consumer's pressures.*—240 V between neutral and principal conductors; 416 V between phases.

---

* 'Consumer's pressure' denotes the pressure at the consumer's terminals declared by the supplier.

† 'Station pressure' denotes the normal pressure applied to the terminals of the transmission line at the generating station or substation.

(ii) Station pressures *—264 V between neutral and principal conductors; 457 V between phases.

(c) *Extra High Pressures.*

(i) Delivered pressures.†—3 000, 6 000, 10 000, 30 000, 60 000, 100 000, 120 000 V.

(ii) Station pressures.*—3 300, 6 600, 11 000, 33 000, 66 000, 110 000, 132 000 V.

The consumer's or declared pressures are the standard pressures, the station pressure being derived in each case by adding to the declared pressure the pressure lost (§ 24) in the line when carrying its full load; unless otherwise specified, this loss shall be assumed to be such as to give the station pressures shown above.

Earlier standards of pressure for D.C. and A.C. systems (given in the third edition of this book, p. 10) will necessarily be represented in existing installations for many years to come. The actual consumer's voltages in different supply areas are given in various annual publications.‡

Pressures up to 232 000 V are already in use for the transmission of power.

24. Loss of Pressure.—In any conductor carrying a current there is a drop of pressure, increasing both as the length and consequent resistance of the conductor increases, and also in direct proportion to the current. Professor Fleming pointed out many years ago that the hydraulic gradient in a water pipe offers an exact analogy to the pressure gradient in a conductor. Between any two points in a pipe line, connected to a reservoir at one end and discharging at the other, there is a difference of 'water motive force' or pressure, urging a flow of so many gallons per sec. (according to the resistance of the pipe) between those points; there is thus a gradual fall of pressure (the hydraulic gradient) all along the pipe. Similarly, along an electric conductor, there is a gradual fall of pressure or pressure gradient; and it is the difference of pressure or potential between any two

* 'Station pressure' denotes the normal pressure applied to the terminals of the transmission line at the generating station or substation.

† 'Delivered pressure' denotes the normal pressure at the terminals of the transmission line at the delivery end.

‡ The most nearly complete list is probably that in the *Practical Electrician's Pocket Book* (Rentell).

points which causes a current to flow, the strength depending on the resistance offered by the conductor. The loss in volts in any part of the circuit is the product of the current in amperes and the resistance of that part of the circuit in Ω. Thus if a uniform wire 100 ft. long has a steady current flowing in it that causes a drop of pressure of 100 V in the whole length, then there will be a drop of 1 V per foot run; this principle is utilised in the potentiometer (§ 95).

By way of example, let it be assumed that 100 A are transmitted from a source of supply to a piece of apparatus by a pair of wires each a mile long, having a total resistance of 0·79 Ω (= No. 3/0 S.W.G. copper wire), then the drop in pressure on the line will, by Ohm's Law, be $0{\cdot}79 \times 100 = 79$ V. If, then, the pressure at the generator is 2 200 V, the available pressure for use at the far end will be 2 121 V. The difference is called the 'lost volts' (especially in the case of the drop of pressure in the conductors or 'windings' of a generator) or simply the 'drop in pressure.' In the case of alternating current supply the problem is less simple than in the above example, and is referred to later (§ 44 and Chapter 14).

Although in a particular case we may be dealing either with the pressure between two conductors or with that between one conductor and 'earth,' the latter case is perhaps the best to consider from the elementary standpoint, as it is also when dealing with 3-phase alternating currents (§§ 302, 313). Just as the pressure or degree of vacuum of air or water is ordinarily reckoned by its departure above or below normal atmospheric pressure, so electrical pressures may be expressed in relation to 'earth potential,' either positively or negatively. There will be a pressure gradient along a wire carrying a current, and it can be measured by voltmeters connected between line and earth at different points, just as a pressure gauge would show different readings at various points along a horizontal water pipe discharging under an imposed pressure. In both cases, the instruments would show a steady static pressure at all points if the flow ceased.

Current.

25. Amperes.—That a clear conception of an electric current or of an ampere is difficult to inculcate is clear from the references, so common in newspapers, to 'currents of 2 000 V' and

the like. Such ideas are survivals from the days before a scientific system of units had been evolved and co-ordinated in Ohm's Law (§ 17). From what has been written above it will be seen that the strength of current in a circuit, in amperes, depends on the other two factors of resistance and pressure. By Ohm's Law, if the standard pressure of a supply is (say) 200 V, a piece of apparatus connected thereto, and taking a current of 1 A, will have a resistance of 220 Ω; and another apparatus, having a resistance of 80 Ω will take $2\frac{3}{4}$ A. A reference, however, to § 17 will show that this is only true of an *unvarying* current, and therefore when alternating currents are being considered the statement requires modification, as explained in due course (§ 44); the meaning of the term 'ampere' when applied to an alternating current is explained in § 29 and the examples following refer to continuous current. A pressure of no matter how many thousand volts may exist between two wires, side by side, but it will produce no flow of current unless and until there is a path or circuit for it from one wire to the other. If there is no such circuit the resistance is infinite and the current zero. For example, a steam engine is driving a large dynamo, maintaining a pressure of 500 V between its terminals, but if the external circuit is not closed there will be no current. If a crowbar is now dropped across these terminals the circuit will be closed; the resistance of the crowbar is so small that the current momentarily flowing will only be limited by the internal resistance of the coils of wire in the generator, and it may amount to many thousands of amperes. The power supplied to this 'short-circuit' from the plant may, for a moment, be enormously in excess of that which either engine or generator is intended to give, or is capable of giving for any length of time, as the whole of the stored mechanical energy of the revolving machinery is dissipated in heat in an instant; and the dynamo—or what is left of it—comes to rest immediately in consequence.

The difficulty that students certainly experience in coming to grips with the ampere as a unit arises no doubt from the fact that it is a complex unit instead of a simple one like the pound or the gallon. As mentioned in the preface to the third edition (p. vii), an exact parallel to the ampere is the term 'cusec' often used in hydro-electric work, representing water-flow at the rate of one cubic foot per second or a 'second-foot.' The ampere

is, properly speaking, a coulomb-second or a flow of the definite quantity of electricity represented by a coulomb (§ 28) per second of time. As ordinarily used, however, the factors are so defined that it appears as though the coulomb were derived from the ampere instead of *vice versa.* This is in fact a much more convenient way in dealing with power problems, while in physics the quantity basis is more generally used.

26. Milliamperes.—When dealing with very small currents it is convenient to have a smaller unit than the ampere, and the milliampere, mA (= one-thousandth part of an ampere) is used. In dealing with voltmeter currents, telegraphy, and electro-medical work this term (or the still smaller micro-ampere = one-millionth ampere) is generally used. Leakage currents in a domestic installation are generally of this order, as shown in the examples in Chapter 40.

27. Currents in Wires; Current Density.—As the pressure of supply is generally a fixed quantity, the power taken by any piece of apparatus (expressed in watts = $E \times I$) will be proportional to the current. The size of the wires used depends primarily on the current they have to carry; if a wire is too small the loss of volts due to its resistance may be such as to effect the use of the apparatus. For example, if a house is supplied at 100 V pressure, and the loss of pressure between the point of entry and a certain lamp is 6 V, that lamp will only get 94 V; if it is designed for 100 V the actual candle-power will not be nearly what it should be. Again, the wire may be overheated if carrying more than its proper current; the amount of the heat developed is proportional to the square of the current, and is exactly commensurate with the watts I^2R dissipated in the conductor. (This is true also of alternating currents.) The cross-sectional area of copper wires is given in the tables (which will be found later on in §§ 280 and 307) in decimals of an inch, so that the current they will carry at 1 000 A per sq. in. 'current density' can be read off directly; thus, area 0·100, current 100, etc. Until recently 1 000 A per sq. in. was generally adopted as the rule-of-thumb limit of safety for the current carrying capacity of wires used in house wiring; now, as the tables referred to will show, it has ceased to be significant, and the permissible current is determined by formulæ with an experimental basis. Obviously a bare wire, or one thinly covered only, will

radiate its heat much more rapidly than a heavily insulated wire (§ 328); and the radiating surface of the insulating covering of a small wire will be relatively greater than that of a large wire, if the radial thickness of the insulation is the same in both cases.

28. **Ampere-hours.**—As shown at the end of § 25 a coulomb is a definite quantity of electricity, comparable to a quantity of any ordinary matter, and it is equal to 10^{-1} absolute C.G.S. units of electricity (*see* Table 1, § 2). In practice, however, it is more convenient to regard the coulomb as the quantity of electricity due to a flow of 1 ampere in one second, *i.e.* an 'ampere-second.' More commonly, quantities of electricity are expressed in 'ampere-hours,' the ampere-hour (1 Ah = 3 600 C) being in fact the practical unit of quantity of electricity.

The term ampere-hour is used in the charging and discharging of batteries, electroplating, or any other electro-chemical process. Take, for example, a battery consisting of three motor-car 'ignition cells,' having a working pressure of 6 V; the pressure, be it noted, is 2 V per cell without any regard to their size (Chapter 18). A particular size, from a catalogue, is stated to have a 'capacity' of 60 Ah. If the working current is kept within recognised limits the 60 Ah could be given by a current of 2 A for 30 hours or 1 A for 60 hours, and so on; the capacity of the cells for discharging would in actual practice be slightly larger as the current decreases and the time increases, but this may be waived for the present. The battery in question would ordinarily be charged at the rate of 4 A for a period of about 15 hours, after a complete discharge within the allowable limits. This affords an opportunity for another illustration of the working of Ohm's Law. Suppose that the owner desires to buy a small generator for charging these cells. Now the pressure of the three cells, as stated above, is 6 V, and this pressure is a 'back E.M.F.' in direct opposition to the pressure of the generator. If therefore the latter were incapable of a greater pressure than 6 V the two pressures would exactly balance, and no current would flow. In point of fact the generator pressure would, towards the end of the charging process, have to rise nearly to 9 V in order to force 4 A through the cells. There is no contradiction of Ohm's Law here; the effective pressure E is in this case the *difference* between the two opposing pressures of generator and cells, and it must be sufficient to overcome the resistance R made up of the internal resistance of the cells and

the external resistance of the circuit; *i.e.* $I = (E - e)/(R + r)$. Returning, after this digression, to the consideration of ampere-hours, let us assume that the applied pressure in any particular case is sufficient to overcome the opposing pressure of the cell or plating bath, etc., so that a current will flow through the latter; the total electro-chemical effect of this current then depends on the number of ampere-hours. For example, the international definition of an ampere, already referred to in § 3, states that under the conditions laid down it will deposit silver from silver nitrate at the rate of 0·001 118 of a grm. per sec. or 4·024 8 grms. per hour.

The weight of metal deposited electrically from a solution per ampere-second or coulomb is different for different metals, but is a physical constant (the 'electro-chemical equivalent') for each particular metal. (*See* Chapter 38.)

Effective, Virtual, or R.M.S. Values.

29. Effective Value of a Varying Pressure or Current.—An unvarying electric current or pressure is easy to define (§ 3), but there is an obvious difficulty when we come to consider an alternating current or pressure the instantaneous values of which rise from zero to a positive maximum, decrease to zero, rise to a negative maximum, and again return to zero (§ 11). The algebraic average of a symmetrical wave is clearly zero; in other words, as much current flows in one direction during one half-cycle as flows in the other direction during the next half-cycle. For this reason alternating current as such is useless for electro-chemical work (battery charging, electroplating, etc.) which depends upon quantity (ampere-hours) of electricity flowing in a definite direction (§ 28). If, however, the alternating wave be 'rectified' (§ 13 and Chapter 17) we obtain a more or less discontinuous unidirectional current, the effective value of which for electro-chemical purposes is represented by the mean ordinate of the rectified wave. This is the only connection in which the mean or average value of an alternating wave has any practical importance, and it will be seen that it is the average value of the half-wave which is then of importance—not the average of the complete wave, which is zero.

The heating effect of an electric current varies with the square of the current (§ 49) and, in general, the power dissipated by an

unvarying current I (amperes) flowing through a resistance R (ohms) is: W (watts) $= I^2R$ (§ 17), *i.e.* the power varies with the square of the current. For this reason, the effective value of an alternating current is defined as being numerically equal to the unvarying (direct) current which produces the same heating. A hot-wire ammeter (§ 99) is equally correct for measuring continuous or alternating currents.

Referring to Fig. 6, I represents an alternating current of ideal, sinusoidal wave form. The power or heating corresponding to any instantaneous current i (*whether positive or negative*) is proportional to i^2 and is always positive, *i.e.* the curve I^2 represents instantaneous heating effect and consists of a series of positive loops. The mean ordinate of I^2 is represented by the line I_e^2 and represents the 'mean-square' value of the current I. Taking the square root of I_e^2 we obtain I_e the 'root-mean-square' value of I, and this is clearly the value of the unvarying current which produces the same heating as the alternating current I. In other words I_e is the 'effective' value of the alternating current, and is sometimes called the 'virtual' value or the 'root-mean-square' (R.M.S.) value. The term root-mean-square is best, in that it is self-explanatory.

The R.M.S. value of any wave form may be found by the above-described combination of graphical and numerical working, but the wave forms of all commercial A.C. supplies are close approximations to a sine wave, the average and effective values of which are geometrical constants.

30. Average and Effective Values of Sine Waves.—The *average value* of any sine wave, *i.e.* the arithmetical average of its instantaneous ordinates throughout a half-cycle, is equal to its maximum value $\times\ 2\ /\ \pi$. Thus, referring to Fig. 6,

$$I_a = 2I_m\ /\ \pi = 0{\cdot}64I_m \text{ (nearly)}.$$

The useful value of the alternating current I, when rectified, for electro-chemical work would be $0{\cdot}64I_m$ if both half-cycles were utilised, and $\frac{1}{2} \times 0{\cdot}64I_m = 0{\cdot}32I_m$ if only the alternate half-cycles were utilised (*see also* Chapter 17).

The *effective, virtual or R.M.S. value* of any sine wave is equal to the maximum value $/ \sqrt{2}$. Thus, in Fig. 6,

$$I_e = I_m\ /\ \sqrt{2} = 0{\cdot}707I_m.$$

The *form factor* of any periodic wave is defined as the ratio

of its effective to its average value, hence the form factor of a sine wave

$$= \frac{I_m}{\sqrt{2}} \times \frac{\pi}{2I_m} = \frac{\pi}{2\sqrt{2}} = 1{\cdot}11.$$

The form factor is a useful means of comparing different wave forms (*see also* § 34). Another factor, which is also useful in this connection, is the *peak* or *crest factor*, *i.e.* the ratio of the maximum to the effective value of the wave. The crest factor of any pure sine wave is $\sqrt{2} = 1{\cdot}414$. The crest factor of the A.C. voltage used to test cable insulation should not exceed 1·5.

Table 5 gives an instructive comparison between the above-mentioned constants for different wave forms. In practice, wave forms are generally determined by oscillograph (§ 118).

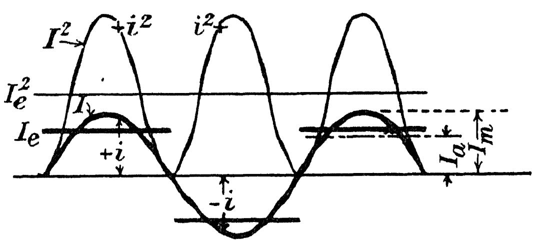


FIG. 6.—Effective value of alternating current.

TABLE 5.—*Constants for Different Wave Forms.*

Wave Form.	Average Value (Half-cycle).	Effective Value.	Form Factor.	Crest Factor.
Sinusoidal .	Max × $2/\pi$ = max × 0·64	Max/$\sqrt{2}$ = max × 0·707	1·11	1·414
Rectangular .	Max × 1·00	Max × 1·00	1·00	1·00
Triangular .	Max × 0·5	Max × 0·577	1·15	1·74
Semi-circular	Max × 0·785	Max × 0·816	1·04	1·23

31. **Maximum Pressure and Current.**—While the minimum value of a sinusoidal alternating pressure or current during each period is zero, the maximum instantaneous value is the virtual or 'root-mean-square' value multiplied by $\sqrt{2}$ or 1·41. In the case of alternating pressures the maximum value is important, as, although only instantaneous, it tends to break down the insulation of the circuit (§ 298). Thus if the pressure is said to be 220 V —*i.e.* the virtual or root-mean-square pressure as shown by a

correctly calibrated voltmeter—then the maximum value will rise, twice in each period, to $220 \times \sqrt{2}$ or 312 V. If the wave is more pointed than a sine wave the maximum value may even be considerably higher (see Table 5). The maximum value is also of importance in relation to electric shock, for at the same virtual pressure of supply the shock pressure obtained on an alternating circuit is $\sqrt{2} = 1{\cdot}4$ times that on a continuous current system with the corresponding effective pressure.

MAGNETIC EFFECTS OF ELECTRIC CURRENT.

32. **Permanent and Electro-magnets.**—The familiar 'horseshoe' magnet is constructed of hardened steel, and when once magnetised retains its power of attracting iron or steel more or less indefinitely. It is used in certain classes of electrical measuring instruments and in 'magneto' generators, etc. Annealed iron and certain steels, on the other hand, are incapable of retaining magnetism, although they can be very powerfully magnetised by suitable means involving the expenditure of power. If a number of turns of insulated wire are wound round a soft iron core, and a current is then passed through this 'magnetising coil,' the core becomes strongly magnetic for so long as the current is flowing. By varying the intensity of current the strength of the magnetism can be altered (§ 42); in the case of alternating current the magnetism is constantly altering (§§ 34, 39). When the current ceases the magnetism almost entirely disappears. Into the elements of magnetism it is not necessary to go, as this knowledge is assumed; it must, however, be pointed out that a magnet must necessarily always have a north-seeking pole and a south-seeking pole, whatever its shape or construction. If it is an electro-magnet the relation between the polarity and direction of the magnetising current is fixed, and will be seen at once from Fig. 7, from Professor Thompson's *Elementary Lessons*. It matters nothing whether the turns are wound right- or left-handed, or what the shape of the iron core is. The arrows show the direction of the current, from + to −; or positive to negative.

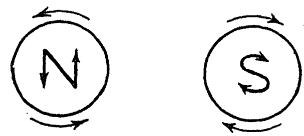


FIG. 7.—Polarity of electro-magnet.

A wire, whether straight or bent into a loop, always creates a magnetic field around it when it is carrying a current, and an iron

core serves to augment the strength of this magnetic field. In considering the field created by a wire, Maxwell's 'corkscrew rule' is useful, and it will be found to apply to the conditions shown in Fig. 7. The rule runs: The direction of the current (from + to −) and that of the resulting magnetic force (from N. to S.) are related to one another as are the rotation and forward travel of an ordinary right-handed corkscrew. An alternative means of memorising the relationship between polarity and direction of current circulation is provided by the fact that arrow-heads (directed outwards) on the tails of the letters N. and S. indicate the direction of current rotation producing north and south polarity respectively.

This magnetic effect in conductors is by no means negligible. A case cited in § 327 shows that it may have serious effects on overhead lines, and it is a factor of primary importance under short-circuit conditions (§ 338). It frequently gives rise to errors in electrical instruments placed too near switchboard conductors carrying heavy currents (§ 92). It also causes the apparent rise of resistance known as skin effect (§ 38 and Chapter 35), which is most marked in steel conductor rails on electric railways.

Apart from the use of electro-magnets in dynamo-electric machinery and instruments, they are also used extensively for their direct effect in attracting iron or other paramagnetic metals; the practical applications vary from lifting magnets (Chapter 31), for raising girders and the like, whether on land or below water, to the extraction of splinters from the human body. Until recently the latter use was mainly confined to the oculist, but of late giant electromagnets, taking several kilowatts, have been used in hospitals for extracting shell-splinters and ferro-nickel cased bullets. While iron and steel are by far the most important, there are other metals, especially nickel and cobalt, which are paramagnetic in a less degree; substances which are repelled from a magnet are called diamagnetic, and include bismuth, antimony, and many others.

33. Polarity (Direction of Flow) of Current.—The direction of a current is a matter of convention, for the work of the engineer is not seriously affected by the truth or otherwise of the modern electronic theory of matter, and it matters little to him whether there is an actual transfer of corpuscles or merely a molecular or ultra-molecular vibration around the conductor. The adopted

convention concerning the direction of current flow arose from the consideration of the primary cell, and is explained in that relation in § 127. The positive pole of any other generator is taken to be that which behaves in the same way as the positive pole of a battery. Since the current in any conductor produces a magnetic field, it will, like any other magnet, deflect a compass needle to one side or the other according to its polarity. This property enables the conventional direction to be determined by Ampère's rule, *viz.:* Suppose a man swimming in the wire with the current, and that he turns so as to face the needle, then the North-seeking pole of the needle will be deflected towards his left hand. A useful old mnemonic in this connection is Crompton's SNOW rule; *viz.:* Place a compass needle under a wire placed in the meridian, and the current entering at South turns the **N**orth-seeking pole of the needle **O**ver to **W**est.

34. **Hysteresis.**—If a core be magnetised by alternating current it is alternately magnetised in one direction, demagnetised on the reversal of the current wave, and then magnetised in the opposite direction. These cycles continue so long as the current is maintained, and have the same periodicity as the current, *i.e.* generally 50 cycles per sec. (§ 12); but the magnetic changes lag slightly behind the current reversals. The abrupt reversal of the direction of the magnetism, involving a change in the molecular arrangement of the iron, involves also a certain expenditure of power known as the 'hysteresis watts.' The energy so wasted heats up the iron core. Such losses occur in transformers and all alternating current machinery, and to a lesser degree in continuous current machines (in those parts of the magnetic circuit which are subjected to varying or alternating magnetic flux).

The power dissipated by hysteresis is proportional to the frequency (cycles per sec.) and varies approximately with the 1·6th power of the maximum flux density in the iron. Since the *maximum* flux density is here involved the hysteresis loss is affected by the form factor (§ 30) of the voltage wave; the hysteresis loss is less with a peaked wave than with a flat-top wave for the same effective voltage.

35. **Induction.**—So long as the magnetic field of a conductor, or a solenoid, or an electromagnet is steady and uniform in value, it produces no E.M.F. in its own or any neighbouring circuit at rest in relation to it; but as soon as there is a change in the

strength of the field, no matter how it is produced, an electromotive force is set up in every conductor within the varying field. In a continuous current circuit, such an E.M.F. can only be produced by varying the strength of the current or by moving one of the elements in the circuit in relation to the other; but with alternating current there must necessarily be induced a continually varying E.M.F., whether the elements of the circuits are stationary or in relative motion. Thus when a conductor is moved across the lines of force of a magnet or *vice versâ* (as in a generator, § 132) an electromotive force is 'induced' in the conductor; and if the conductor makes a closed circuit, a current flows in it in consequence of this pressure. Again, if a conductor is wound upon an electromagnet [as in a transformer (Chapter 17) or induction coil] and the strength of the magnetism alters (§§ 32, 34), an E.M.F. is induced. Similarly each of two conductors carrying currents varying in magnitude will mutually induce an E.M.F. in the other; and a varying current in a single conductor will induce a secondary E.M.F. in opposition to itself. In all such cases except the last there is no metallic connection between the circuits; the electromagnetic induction takes place across an air-gap. The essential condition is that the wire in which an E.M.F. is induced shall cut, or be traversed by, varying magnetic lines of force.

The relation between the lines of force, direction of motion, and direction of induced current is given by the following rule:* Extend the forefinger and thumb of the *right* hand at right angles, and the middle finger at right angles to the plane containing the forefinger and thumb; then, if the forefinger be set in the direction of the magnetic field (N. to S.), and the thumb in the direction of motion, the middle finger will indicate the direction of current flow (+ to −).

This property of self-induction has been compared with inertia; it is that property of electricity which causes it to resist any change in its rate of flow. It will be seen that three separate

* *Note.*—This useful rule was devised many years ago by Fleming, together with the mnemonic: 'FORefinger, force; thuMb, motion; mIddle, induced.' As thus used with the *right hand*, the rule covers induction of current in a moving conductor, *i.e.* is a dynamo rule. If the *left hand* be used in the same way the fingers and thumb give the relation for a current-carrying conductor moving in an electric field, *i.e.* for a motor.

cases may arise. First we have the induction in a single conductor due to a magnetic field around it, which is for some reason varying, but with which we are not for the moment concerned; secondly, the mutual induction of two conductors each affecting the other; thirdly, the self-induction of a conductor on itself, which corresponds to inertia in matter. In every case, as with mechanical reactions, the tendency is for the induced E.M.F. to resist the change which produces it. A concrete example, which can be put to the test, is ready to hand in the field magnets of an ordinary shunt-wound generator, or any other large electromagnet. If the full pressure the coil is intended to bear is applied suddenly to the terminals, the growing field produces a counter E.M.F. opposing the applied E.M.F., and it is some seconds before the current attains its full strength. On the other hand, if the circuit be opened suddenly when the magnet is at full strength, the field cannot vanish immediately. As it dies down, it produces an E.M.F. tending to keep the current going. This E.M.F. may be enormously in excess of the applied E.M.F., and may cause a serious arc at the switch contacts, or even break down the insulation of the field coils. If the operator is careless he may receive a most unpleasant shock in this way from a circuit which, in ordinary working, could be handled with impunity.

It follows from what has been written above that if two wires close together are carrying the same current in opposite directions, their magnetic and inductive effects balance and neutralise one another. This fact is utilised to prevent induction in telegraph or telephone lines carried near power circuits (§ 335). If it is desired to wind a coil of wire that shall be 'non-inductive,' the wire is doubled from the middle point, bringing the two ends together; it is wound thus on the bobbin, so that each turn consists of two mutually antagonistic wires carrying the same current in opposite directions.

36. **Unit (Henry) of Induction.**—The self-induction of a winding or circuit, or the mutual-induction between two windings or circuits, is generally expressed in terms of the E.M.F. induced by a change in current at the rate of 1 A per sec., the unit of self- or mutual-induction being the 'henry.' Thus the self-induction of a circuit is 1 henry if current changing at the rate of 1 A per sec. induces an E.M.F. of 1 V opposing the current change. Similarly, the mutual induction of two circuits is

1 henry if current changing in one circuit at the rate of 1 A per sec. induces an E.M.F. of 1 V in the other circuit.

An alternative definition is that the self-induction of a circuit is numerically equal to the number of 'linkages' per ampere, divided by 10^8. The 'linkage' = number of magnetic lines × number of turns in coil, etc., with which they are linked. Both definitions lead to the same result.

37. Wattless Currents.—In a D.C. circuit, current flow inevitably involves power expenditure (§§ 17, 48), but this is not necessarily the case in an A.C. circuit. In a choking coil (§ 45), for instance, the effect of self-induction (§ 35) is to cause the current wave to lag nearly 90° out of phase with the pressure wave. Similarly, the primary coil of a transformer or auto-transformer, although connected directly across the full supply pressure, only takes power in proportion to the power drawn off at the secondary. If the secondary circuit is open, so that no current is flowing in it, then the choking effect of self-induction causes the primary current wave to be almost 90° out of phase with the primary pressure wave; the current is there, and is magnetising the core at each cycle, but the algebraic or vectorial product of the opposing waves of pressure and currents amounts to very little in true watts (§ 56). When such conditions obtain, the current is said to be a 'wattless current'; the volt-amperes may have a high value and yet the true watts in the circuit may be negligible. The importance of this peculiarity will be seen when dealing with A.C. transmission of power (Chapter 14).

The diagrams in Figs. 8 and 9 illustrate the distinction between watt and wattless currents. (*See also* §§ 56, 154.) Fig. 8 represents the case where there is only ohmic resistance present in one phase of an alternating current circuit; consequently the current wave is in step or 'in phase' with the pressure wave and the power is the product of volts and amperes, as shown by the tall curve. In the first half-cycle both current and pressure are positive, while in the second half both are negative, so that the product is in both cases positive. In Fig. 9 the other limit is reached and the current lags 90° behind the pressure. The resulting power curve, obtained by the product of corresponding instantaneous values of pressure and current, is partly positive and partly negative, in quarter cycles; the power consumed during one quarter cycle is returned to the circuit in the next.

It will thus be seen that the generator or transformer must be built to generate and withstand the full pressure; its coils must be able to carry the full current; the I^2R losses are occurring as usual; but the useful output is nil. (*See also* Chapter 5.)

38. Skin Effect.—Any current-carrying conductor may be regarded as consisting of a number of filaments, each carrying part of the total current and each producing round itself a magnetic field which 'links' (§ 36) with other filaments in the conductor. The number of linkages is greater for the central filaments than for the filaments in the surface or skin of the conductor, hence the self-induction is greater for the central filaments, and there is a tendency for current to concentrate in the outer layers of the conductor. As a result, the effective resistance of the conductor is greater to alternating current than

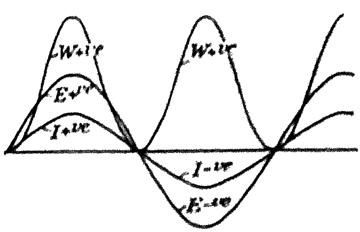


Fig. 8.—Current and voltage in phase.

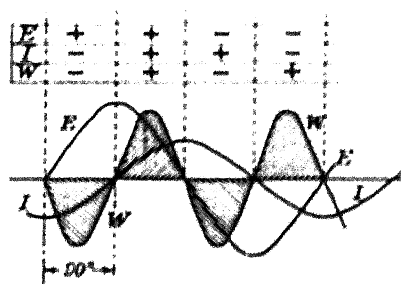


Fig. 9.—Current 90° out of phase with voltage.

to direct current, quite apart from the question of reactance (§ 44). This so-called 'skin effect' is more pronounced in magnetic conductors (*e.g.* steel wires and rails; § 309 and Chapter 35) than in non-magnetic conductors, because the self-induction is greater in the former case. For the same reason, skin effect is more pronounced the larger the cross-section of the conductor and the higher the frequency of the current. At very high frequencies, such as those concerned in lightning discharges, skin effect increases the effective resistance to such an extent that the high frequency current will break down an air-gap (leading to an earth connection, § 346) rather than flow through a reactance coil which offers very low resistance to direct current or to alternating current of commercial frequency.

39. Eddy Currents.—An E.M.F. is induced in any conductor

situated in a varying field (§ 35) whether the variation is due to the conductor moving from one part of the field to a part where the magnetic flux density is greater or smaller, or whether the variation is due to variations in the value of current in a neighbouring conductor. If the conductor in which the E.M.F. is induced forms part of a regular electric circuit there is a definite current flow in the latter, but if the conductor is simply a mass of metal—such as an armature core, an iron girder, or a metal tank or case—the induced E.M.F. causes currents to circulate locally in the metal, these currents being aptly termed 'eddy currents.' The magnitude of the induced E.M.F., and therefore of the eddy currents, is greater the stronger the magnetic field and is therefore increased by the presence of iron. Also, for given field variation, the E.M.F. induced is greater the higher the frequency. The eddy current produced by given induced E.M.F. is lower the higher the resistance of the path through which the current flows. One method of reducing eddy currents is therefore to use material of higher electrical resistance for the parts concerned. For this reason high electrical resistance is desirable in the sheets used for armature and transformer cores (§ 82). The eddy currents are dissipated in the form of heat and the loss which they occasion varies with I^2R (§ 49), hence reducing the current I reduces the loss to a greater extent than it is increased by the increase in resistance R.

Eddy currents are induced in conductors carrying alternating current as well as in all adjacent metal. They may produce a dangerous degree of heating, they may cause errors in instrument readings, and in all cases they represent wastage of energy. A useful application of this is to be found in the 'eddy current brake,' which is often used as an artificial load when testing electric motors. Eddy currents are induced in a metal disc driven by the motor and the energy dissipated by these currents constitutes a load for the motor. Under ordinary circumstances, however, eddy currents are objectionable, and they may be reduced by excluding iron (where possible) from the path of the varying field, by using non-magnetic material where applicable (§ 84), and by interrupting or reducing the cross-section of the paths for eddy current flow by saw-cuts. If mechanical continuity be required the saw-cuts are filled with insulating material. Eddy currents in armature and transformer cores are

reduced by building the latter from thin sheets of special steel (§ 82) insulated from each other by varnish or paper. The plane of the sheets is parallel to the direction of the main field so as not to interrupt the flow of the latter. The laminations are clamped together by bolts which are insulated to prevent short-circuiting the laminations. If slots, etc., in the laminations be filed the laminations may be short-circuited by particles of metal, and the relatively heavy current flowing through these particles may cause such heating as to damage the insulation on adjacent windings.

Magnetic Circuits.

40. Magnetic Field.—A magnetic field is the region round a magnet or current-carrying conductor (§ 32) within which magnetic effects are exerted on magnetic materials (§ 32) or electrical conductors. The unit strength of magnetic field (Table 1, § 2) is represented conventionally by 1 line (of magnetic flux) per sq. cm.; this, the unit of 'flux density,' is termed the 'gauss.' *

In every magnet a north pole is necessarily associated with a south pole and similar conditions obtain in the magnetic fields established by electric currents, so that magnetic flux has always a closed magnetic circuit. Unlike the electric circuit, the magnetic circuit cannot be 'opened' because, although some substances have a higher permeability (or magnetic conductivity) than others, there is no magnetic insulator.

41. Magnetic Circuits.—The magnetic circuit of a permanent magnet consists of the metal of the magnet itself and the air path between its poles; the 'magnetomotive force' (M.M.F.) driving the flux round this path is determined by the pole strength of the magnet. Such circuits are found in permanent magnet generators ('magnetos') used for medical purposes, for ignition, and for small lighting sets, but in motors and generators for commercial supply the magnetic circuit comprises the field and armature cores and the small air gap between them, whilst the M.M.F. is provided by electromagnets (the field cores and their windings).

In any magnetic circuit the conditions are largely analogous to

* There is a field of 5 gauss at 40 cm. from a very long straight conductor carrying 1 000 A, the return conductor being a long way off. A field of 10 gauss is produced at and near the centre of a plane circular coil 100 cm. diameter and of 800 ampere-turns (§ 42).

those in an electric circuit, and may be stated in a form similar to Ohm's Law, *viz.*:—

$$\text{Flux} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}}.$$

The magnetic flux, or total number of 'lines of force' in the magnetic circuit, corresponds to the current. The magnetomotive force, corresponding to E.M.F., is proportional to the pole strength in the case of permanent magnets and, in the case of electromagnets, is proportional to the ampere-turns on the magnet, upon which the flux depends. The reluctance is the resistance of the magnetic circuit to the passage of the lines of force and is not a constant of the circuit, but varies with the degree of magnetic saturation (§ 43).

42. **Magnetomotive Force: Ampere Turns.**—In any form of apparatus using electromagnets the phrase 'ampere-turns' is used for the product of the current in amperes and the number of complete convolutions or turns of the wire carrying it. This is the practical unit of magnetomotive force. The magnetomotive force (in 'gilberts') produced by a solenoid of T turns carrying a current of I amperes is given by the formula $4\pi IT/10$ and thus increases indefinitely in direct proportion to both the current and the number of turns. Due to increasing reluctance (§ 43), however, the strength of field produced is not proportional to the current when the iron approaches magnetic saturation.

Under all practical conditions the magnetising effect of a certain number of ampere-turns is the same whatever the value of the terms I and T in the constant product IT; thus 100 turns of a wire carrying 1 A will have the same magnetising effect on a bar of iron within the coil as a single turn carrying 100 A; in each case there are 100 ampere-turns.

43. **Reluctance.**—The reluctance of a magnetic circuit corresponds to the resistance of an electric circuit. It increases in proportion to the length of the circuit and varies inversely with the cross-sectional area of the circuit. Whereas 'specific resistance' (§ 18) is used as a measure of the resistance offered by various materials to the flow of electric current, the corresponding term used in connection with magnetic circuits is 'permeability' which is analogous to the conductance (§ 18) of an electric circuit. The permeability, μ, of a material is defined as the ratio of the flux density (or 'magnetic induction'), B, produced in that

material to the flux density, H, produced in air by the same magnetising force: *i.e.* $\mu = B / H$. The permeability of iron may be several thousand times that of air (which is taken as unity), but the permeability varies with the kind of iron (§§ 81-84) and with the flux density therein, *i.e.* with the degree of magnetic saturation.

In the case of a solenoid or a coil of wire without any magnetic core, the strength of the field produced is proportional to the current, *i.e.* to the number of ampere-turns, without any limit; but when an iron core is inserted in the coil this proportionality drops as the core becomes incapable of further saturation, until at last the increase is only that due to the coil alone. Thus according to the requirements of each case an electromagnet may be designed to work either saturated, or approaching saturation, or at a point where the change in the current produces the maximum change in the field strength.

The reluctance, S, of a magnetic circuit is given (in 'oersteds') by the formula: $S = l / (a\mu)$; where l = length of magnetic circuit in cm.; a = cross-section of circuit, in sq. cm.; and μ = permeability *at the flux density produced in the iron.* Because of the variation in permeability with the flux density, the flux produced by a given number of ampere-turns can only be determined by successive approximations. It is necessary first to determine approximately the flux in order that a suitable value of permeability may be assumed. On the other hand, the ampere-turns required to produce a certain flux in a certain circuit can be determined at once because the flux density is known and the corresponding permeability can be taken from tables or curves for the material concerned (§ 82).

The reluctance of a composite magnetic circuit consisting of parts of lengths $l_1, l_2 \ldots$; cross sections $a_1, a_2 \ldots$; and permeabilities $\mu_1, \mu_2 \ldots$ is given by—

$$S = \frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots$$

Knowing that the M.M.F. is $4\pi IT / 10$ (§ 42) we have the flux, Φ, given by—

Flux. $$\Phi = \text{M.M.F.} / S \text{ (§ 41)}$$

$$= \frac{4\pi IT / 10}{\left(\frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots\right)}.$$

As the practical problem is generally to determine the ampere-turns, IT, required to produce stated flux, this formula may be put in the form—

$$\text{Ampere-turns,} \qquad IT = \frac{10}{4\pi}\Phi\left(\frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots\right),$$

$$= 0{\cdot}8\ \Phi\left(\frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots\right).$$

Note.—It is usual in practice to plot curves between B and $\frac{10H}{4\pi}$ (*i.e.* the ampere-turns per cm. length, for $\frac{10H}{4\pi} = \frac{10}{4\pi} \cdot \frac{4\pi IT}{10l} = IT/l$). From such curves (Fig. 13, § 81) it is possible to read off at once the ampere-turns required per cm. length of the material concerned, to produce a flux density B in that material.

In most cases a magnetic circuit consists mainly of iron or special steel with an air-gap; as *e.g.* in a motor or generator, where the circuit runs from the north pole of the magnet, across the air-gap, through the iron core of the armature, across the air-gap again to the south pole of the magnet, and thence back to the starting-point through the yoke. The air-gap greatly increases the reluctance, and is therefore reduced to as small dimensions as may be practicable. Some lines of force will inevitably pass from pole to pole without going through the armâture core, and will therefore produce no useful effect; these constitute 'magnetic leakage.'

Ohm's Law for A.C. Circuits.

44. Resistance, Reactance, and Impedance.—Ohm's Law as stated in § 17 is only applicable when the resistance, electromotive force and current are unvarying. The law can be applied to all direct-current circuits if both internal and external resistance be taken into account (§ 21) and if allowance be made for back-E.M.F., where present (§ 28), but it can rarely be applied to alternating current circuits in its simple form, because the effective resistance to current flow in an A.C. circuit is generally greater than the ohmic resistance of the circuit.

The resistance of a conductor in ohms is an inherent property of the material, and is independent of the direction of the current and of its variations; but when dealing with alternating currents another factor comes in, called 'reactance,' which has the effect of apparently increasing the resistance—so that Ohm's Law as stated in § 17 requires to be modified. In explaining the term 'induction' in § 35 the fact is brought out

that, where the value of the current in a conductor is alternating, an E.M.F. is induced, and that this E.M.F. tends constantly to oppose the current which brought it into being, and so to reduce its value; this property may be compared in its effects with inertia in ordinary matter. With a steady continuous current there is no such action. This opposing E.M.F. differs in phase from the current inducing it, so that it has the effect not only of reducing that current in amount but also of altering its phase in relation to the main or 'impressed' pressure wave. A reference back to Fig. 1 (§ 11) may help to explain matters. The dotted line in that illustration shows the sine wave of an alternating current, produced by the impressed E.M.F. shown in the full curve. At the moment the current wave is at a crest, whether positive or negative, the rate of change of its instantaneous value is practically nil, and therefore the change of field strength produced by it is nil, so no E.M.F. of self-induction is being generated. If, therefore, the wave of induced counter-E.M.F. were plotted, it would be on the zero line at each crest of the current wave. On the contrary, at the moment when the current wave is crossing the zero line its rate of change, and consequently that of the field produced also, is at the maximum; hence at these points the wave of counter-E.M.F. would be at its crest. Furthermore, as this E.M.F. opposes the current producing it, it will be rising towards a positive maximum when the current is falling towards zero, and descending towards zero when the current is rising to a negative maximum.

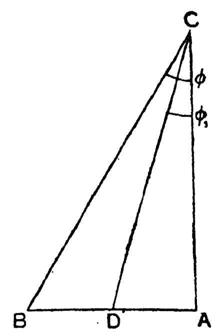


FIG. 10.—Graphical diagram of alternating E.M.F. and resistance.

A graphical representation will help to make the matter clearer. In the right-angled triangle ABC (Fig. 10) AC represents the E.M.F. required to send the current through the ohmic resistance of the circuit, and AB represents the E.M.F. required to send the current against the self-induction or reactance of the circuit. Then CB will represent, on the same scale, the total E.M.F. which must be applied, in order to produce the given current against the total 'impedance,' or apparent resistance, of the circuit. The angle ϕ is the angle of lag of the current behind the E.M.F.

Similarly, by altering the scale, the three sides will represent

true or apparent resistance, since the resistance is the E.M.F. divided by the current in the circuit. On this basis AC represents the ohmic resistance of the circuit and AB represents the reactance, or apparent resistance due to self-induction; consequently BC represents, on the same scale, the total 'impedance' or apparent resultant resistance of the circuit, which will take the place of R in Ohm's Law. Whether the sides of the triangle represent volts or ohms, we have that: $BC = \sqrt{(AB^2 + AC^2)}$. When dealing with resistance values this may be expressed—

$$\text{Impedance} = \sqrt{\text{resistance}^2 + \text{reactance}^2}.$$

The value of the reactance (expressed in ohms) is $2\pi fL$, where f is the number of periods per second, or the frequency and L is the coefficient of self-induction, expressed in henries; the value of L is worked out in the case of transmission lines in §§ 299 and 302 where the formula will be found. In practice, inductance is generally expressed in millihenries = 1 / 1 000 of a henry (mH).

For a circuit containing only resistance and inductance Ohm's Law becomes—

$$I = \frac{E}{\sqrt{[R^2 + (2\pi fL)^2]}}.$$

If there is also capacity in circuit an additional term is required in the denominator of the fraction, as explained in § 46.

In some cases, *e.g.* where rapid variation of the field current of a motor or dynamo is required for purposes of speed or voltage control, it is necessary to take into account the fact that the current in an inductive circuit does not instantly assume the steady value corresponding to the applied voltage. If a constant D.C. voltage E be applied to a circuit of constant resistance R ohms and constant inductance L henries, the value (in amperes) of the current t seconds after closing the circuit is: $I = \frac{E}{R}(1 - \epsilon^{-ut})$; where ϵ = the base of natural logarithms = 2·718 approx.; and $u = R / L = 1 /$ (the 'time constant' of the circuit). The '*time constant*' = L / R, and is the time required for ut to become unity; the current then $= (E / R)(1 - \epsilon^{-1}) = (E / R)[1 - (1 / 2\cdot718)] = (E / R)(1 - 0\cdot368) = 0\cdot632\, E / R$ or 63·2 % of the steady current E / R.

Similarly, the time constant of a circuit containing a capacity C farads in series with a resistance R ohms is RC seconds, and is the time required for the voltage and charge of the condenser to reach 63·2 % of their steady values.

The greater the time constant of a circuit the longer it takes for steady conditions to be reached after applying an E.M.F. or changing the applied E.M.F.

45. Choking Coils.—It will be seen from the expression for impedance in the preceding paragraph that a circuit may have

high impedance (*i.e.* high effective resistance) to alternating current though the ohmic resistance is very low. This is a fact of the highest practical importance. In a circuit of high impedance but low resistance, *i.e.* in a circuit which is practically all reactance: (i) There will be high voltage drop (given by $2\pi fLI$ (§ 44) if R be taken as zero) but very little dissipation of energy because the current is practically 90° out of phase with the voltage; *see also* § 37. (ii) Little opposition is offered to the flow of direct current, which is obstructed only by ohmic resistance and is unaffected by reactance. (iii) Less opposition is offered to the flow of low-frequency A.C. than to that of high-frequency A.C. because the reactance ($2\pi fL$) increases in proportion to the frequency. These three facts all find application in practice, as explained below.

A 'choking coil' consists of a winding of relatively low ohmic resistance with an iron core, which causes the inductance and therefore the reactance of the winding to be high. The reactance of the coil may be varied by altering the extent to which the core is inserted within the winding. Such a choking coil may be used instead of a ballast resistance in series with arc lamps (Chapter 25) or, in general, it may be used to reduce the effective voltage in any A.C. circuit practically without loss of energy. The actual dissipation of energy is given by I^2R (§ 49), hence R should be kept as low as possible. Another application of choke coils is to obstruct high-frequency discharges (as in lightning protection, § 346). For this purpose the coil is connected in series with the line carrying the normal current (D.C. or A.C. of commercial frequency). In order that it may cause only low-pressure drop its resistance and (in A.C. service) its reactance are kept low. This is done by using only a few turns of large wire without an iron core. Though the reactance is very low when $f = 50$ or 100 cycles per sec., as in commercial supply, it is very high at the high frequencies of lightning and similar surges, hence the latter find it easier to jump an air gap (provided for the purpose) and flow to earth than to penetrate the choking coil and reach the circuit which this coil protects.

46. Capacity and Condensance. Capacity in a circuit is that property in virtue of which a charge of electricity can be stored up in it in the form of electrostatic stress. Thus such a stress exists between the two coatings of a charged Leyden jar or the

two plates of a charged condenser, and when either is discharged a capacity current flows momentarily. A condenser may be compared to an air-vessel on the delivery pipe of a hydraulic ram, storing up some of the energy of each stroke at the moment and then delivering it back to the column of water out of phase with the ram stroke; at each cycle a certain charge of water enters and compresses the air and then is driven out again.

The capacity of a condenser, whatever the form of the latter, varies directly with the effective surface of the plates or electrodes, and the specific inductive capacity of the dielectric, and inversely with the thickness of dielectric between the plates. The *specific inductive capacity* or *dielectric constant* or *permittivity* ϵ of the dielectric is the ratio of the capacity of a condenser using this dielectric to that of the same condenser with air as dielectric. Values of ϵ for various substances are given in Table 7, § 73.

The parallel wires of an overhead transmission line have a certain capacity, depending on their geometrical arrangement (§§ 304-306), and so have the conductors in a cable (§ 311). In these cases the 'charging current,' which is leading 90° in advance of the impressed E.M.F., may be of considerable importance, as will be explained in due course; the capacity in a cable or line is practically equivalent to a very high resistance in *parallel* with the resistance and the reactance of the conductor, so it does not appreciably affect the total impedance.

Where, however, capacity is in *series* with resistance (either alone or with reactance also) it must be taken into account (Chapter 25). If resistance and capacity alone are present, the effect of the leading capacity current is to cause the resultant current to lead, instead of to lag behind, the E.M.F.; *i.e.* the result is exactly the opposite of induction. In Fig. 10, § 44, this would be shown by drawing AB, now the 'capacity reactance' or condensance, still at right angles, but in the opposite sense; and the angle ϕ would be on the opposite side of AC. If both inductive reactance and capacity reactance are in series with resistance they are in direct opposition (180° apart), and as both are expressed in ohms their difference is taken by vectorial or algebraic addition. In Fig. 10, after setting off the inductive reactance, AB, the capacity reactance would be set *back* from B along BA to a point D; and the line DC would then represent the net impedance; and angle ϕ_1 would then be the angle of phase difference, either lagging (as shown) or leading if the capacity

preponderated and D were on the other side of A. In symbols the impedance is expressed as

$$\sqrt{R^2 + \left[2\pi f L - \frac{1}{2\pi f C}\right]^2},$$

where C, the capacity, is expressed in 'farads.' Ordinarily capacities are expressed, for greater convenience, in 'micro-farads' or millionths of a farad (μF); an example is given in Chapter 25 in connection with the use of condensers for electric lighting circuits. If the two reactances exactly balance, the current will be in phase with the E.M.F. and the impedance will be the same as the resistance; this gives the conditions necessary for resonance or syntony in the circuit, which may cause an almost unlimited rise of pressure if the ohmic resistance is low enough.

47. **Resonance or Syntony.**—A combination of inductance and capacity in series has a definite rate of electrical oscillation or frequency of its own, and, if L and K have such a relation that this natural frequency coincides with that of the E.M.F., the E.M.F. rises just as the pendulum increases its swing if struck synchronously. Thus, consider a circuit consisting of a non-inductive resistance R of 5 Ω, an inductance L of 0·5 H, and a capacity C of 5·1 μF, all in series, with an E.M.F. of 100 V impressed on it, and ascertain at what frequency it will be resonant. This condition of 'critical frequency' is found when the inductance and capacity just balance, *i.e.* when $2\pi f L - 1/2\pi f C = 0$. This equation must be solved for f. Substituting the above values for L and C and expressing C in farads, the equation becomes $2\pi f \times 0{\cdot}5 - (1/2\pi f \times 0{\cdot}000\,005\,1) = 0$, from which $f =$ 100 periods per sec. Put in another way, the time interval between the crests of successive waves, or natural frequency, is $2\pi\sqrt{LC}$, which here equals $6{\cdot}28 \times \sqrt{0{\cdot}000\,002\,55}$ or 0·01 sec. giving 100 periods. The wave length, that is the distance between the crests of successive waves, or between points of equal intensity of electric stress, is equal to the velocity of propagation multiplied by the time interval. Taking the velocity of propagation as equal to the velocity of light, the wave length here will be 300 000 000 × 0·01 or 3 000 000 m.

As the two reactances balance at the critical frequency, the current will be simply E/R or $100/5 = 20$ A, and it will be seen

that if it were possible to reduce the ohmic resistance to zero,* the current (and therefore the pressure rise also) would be infinite. In the example chosen, the pressure across the condenser (which might be an underground cable) would be $I/2\pi fC = 6\,280$ V, and the pressure across the inductance would be $I \times 2\pi fL$, giving the same figure. (*See also* § 350.)

The above is a case of resonance of the fundamental frequency of 100 periods found for this circuit; but as the wave of an alternator is not a true sine wave, but contains superposed odd harmonics, these latter may also give rise to the phenomenon, and indeed do so more often in practice. What is, however, a danger to be guarded against in electrical engineering becomes a most valuable aid to the utilisation of high-frequency currents in wireless telegraphy and medical treatment; and it has even been proposed to utilise resonance in the transmission of power to extreme distances up to 1 000 miles by means of 'half-wave' and 'quarter-wave' systems (§ 318).

POWER AND WORK.

48. **Current and Power.**—The practical unit of electrical power (*i.e.* the rate of doing work) is the watt; if a pressure of 100 V, applied to the terminals of any apparatus, causes a current of 2 A to flow in it, then the power used in that apparatus is 200 W, and by Ohm's Law the resistance of the conductor carrying the current will be 50 Ω.

1 watt = 0·001 34 H.P. = 3·41 British thermal units (B.Th.U.) per hour = 0·73 ft.-lb. per sec. = 44·24 ft.-lbs. per min.

Note.—A British thermal unit is the quantity of heat required to raise 1 lb. of water 1° F. It is equal to 0·252 kg.-cal. A kg.-cal. or 'great calorie' is the quantity of heat required to raise 1 kg. of water 1° C. A 'therm' is 100 000 B.Th.U.

49. **I^2R Watts.**—As a general rule, when dealing with the power utilised or expended in heat in any circuit or apparatus, the power is more conveniently obtained by the derived formula (§ 17) Watts = I^2R, which in the above case gives us 4×50 or 200 W as before. This is the *rate* at which energy is being dis-

* Ohmic resistance reduces the peak value of current or voltagé in cases of electrical resonance, just as friction reduces the amplitude of mechanical resonance.

sipated in the conductor, and while part of it will raise the temperature, part will be radiated away. Although the terms are synonymous, it is the custom to confine the use of the phrase I^2R to energy wasted uselessly in any piece of apparatus or in a line, while calling the power usefully employed $I \times E$ or IE. Confusion between power utilised and power lost in transmission is a fruitful source of misunderstanding, and a simple example may serve to remove this. Suppose two conductors to have a difference of potential of 100 V between them, which is maintained by a generator under all conditions: from terminals on these main conductors two wires, each having a resistance of 0·5 Ω, are led to an electric heater having a resistance of 9 Ω. The total resistance in this external circuit will therefore be 10 Ω, and, by Ohm's Law, the current will be 10 A. The total power in the circuit will be EI = 100 V × 10 A = 1 000 W or 1 kW. The power lost in the connecting wires is $10^2 \times 1$ or 100 W, and 10 V are lost in them. The power usefully employed is therefore 90 V × 10 A = 900 W, which brings the total up to 1 kW. This, however, is all dependent on the initial assumption that the generator *constantly maintains* 100 V pressure at the point where the circuit under consideration begins. If it is sufficiently powerful, and is driven by a suitable engine, this will be the case. But although designed to give 100 V pressure, the generator may be incapable of an output of 1 kW. For example, the source of power may be 50 small secondary cells, giving a pressure of 100 V on open circuit. If now the internal resistance of the battery has a value of 1 Ω, the total resistance in the complete circuit becomes 11 Ω, and *by no possibility* can more than 100 / 11 or, say, 9 A flow in it. The example given in § 21 will help to make this clear.

50. Kilowatts.—For convenience, the term kilowatt (kW) is used for 1 000 W in dealing with power on a large scale :—

1 kW = 1 000 W = 1·34 H.P. = 737 ft.-lbs. per sec.* = 56·86 B.Th.U. per min.

746 W = 0·746 kW = 1 H.P. = 550 ft.-lbs. per sec. = 42·4 B.Th.U. per min. = 2·28 lbs. water per hr., raised from 60° F. and evaporated at 212° F.

* This is, strictly speaking, only true at sea-level and latitude 50°. Elsewhere the weight of a mass of 1 lb. varies. Consequently a string of decimals of a kilowatt, etc., is seldom accurate, apart from errors of instruments and other disturbing causes.

The output of a generator is expressed in kilowatts; thus a generator marked 100 V, 50 A would have an output of $100 \times 50 / 1\,000 = 5$ kW. It is useful to remember that 1 kW supplied to a motor will generally produce 1 brake horse-power at the pulley; in large motors the B.H.P. is somewhat higher in proportion.

51. **Electrical Horse-power.**—It has been often noticed that civil engineers, even those high up in the profession, are not clear on the significance of the International horse-power; *i.e.* they believe the *value* of the H.P. to differ according to where it occurs in a chain of conversions, instead of its being always equivalent to energy expended at the rate of 550 ft.-lbs. per sec. It may therefore not be amiss to give two examples employing the constants in the preceding paragraphs, on the basis of an original 1 H.P., premising that the efficiencies assumed would only apply to much larger plant.

First, a turbine utilising 330 lbs. of water per min. under a head of 100 ft., giving 33 000 ft.-lbs. per min., or 1 theoretical (or water) horse-power. Then the turbine, if it has an efficiency of 75 %, will give 0·75 B.H.P. (brake horse-power). If this is used to drive a dynamo with an efficiency of 90 % the latter will then give out 0·675 E.H.P. (electrical horse-power) or say 500 watts. Continuing the chain, this power is employed to drive a motor with an efficiency of motor and transmission of 85 %; the motor will then give out 0·575 B.H.P. This motor drives a pump with an efficiency of 70 %, which will deliver 0·4 H.P. to the column of water. Thus the overall efficiency of the whole chain is $0{\cdot}75 \times 0{\cdot}9 \times 0{\cdot}85 \times 0{\cdot}7 = 0{\cdot}4$ or 40 %, and the whole of the original water could be pumped back up 40 feet of its original fall while 13 200 ft.-lbs. per min. would be recovered from 33 000.

A similar example can be given in steam practice. It will be seen from the constants in § 50 that 1 H.P. is equivalent to 42·4 B.Th.U. per min. The heat contained in 8 or 9 lbs. of coal burnt in 1 min. would be generated at this rate. Owing to the low thermal efficiency of a steam engine, coupled with the losses in the boiler, the indicated horse-power in the engine cylinder would be about 0·22 I.H.P. and the crank shaft would give about 0·2 B.H.P. The generator driven by this would give out 0·18 E.H.P. (134 watts) and if this power were expended entirely in heat it would produce 7·6 B.Th.U. per min. out of the original 42·4 with an overall efficiency of 18 %.

The Continental or metric horse-power is slightly different, being 75 kg.-m. per sec., equal to 736 W. The late Professor Silvanus Thompson advocated the international kilowatt as a preferable unit of power, to replace the horse-power entirely.

52. **Work; Kilowatt-hour; Unit.**—The kilowatt-hour (kWh) is the practical commercial unit of electrical work performed, and

is called a 'Board of Trade Unit' (B.T.U.), or simply a 'unit,' when dealing with the consumption of energy in an installation; the term 'Kelvin' is also used, and has official sanction, but has not found much favour as yet:—

1 kWh or B.T.U. = 1 000 volt-ampere-hours or watt-hours = 1·34 H.P.-hours = 2 656 400 ft.-lbs. = 3 412 B.Th.U. = 22·7 lbs. of water raised from 62° to 212° F. = 3·1 lbs. water raised from 60° F. and evaporated at 212° F.

Obviously either 1 kW for 10 hours or 5 kW for 2 hours will give 10 units.

53. **Horse-power-hour.**—It will be convenient here to give also the equivalents of the practical mechanical unit of work, the horse-power hour:—

1 H.P.-hour = 0·746 kWh = 1 980 000 ft.-lbs. = 2 545 B.Th.U. = 17 lbs. of water raised from 62° to 212° F. = 2·28 lbs. of water raised from 60° F. and evaporated at 212° F.

In calculating the capacity of storage reservoirs for water-power the relations in this and the previous paragraph will be found very useful (*see* example at the end of § 239).

54. **Measurement of Power and Work.**—Watts are the product of current and pressure, and, as the pressure of an installation is usually fixed within narrow limits, the product of this fixed or standard pressure and the amperes will give the power in the circuit in watts at any one time. If the mean power over any given period is found, *i.e.* the product of the standard pressure and the mean current, then this multiplied by the time will give the work done in watt-hours. This may obviously be expressed also as the product of the standard pressure and the ampere-hours.

Most of the domestic supply 'meters' on continuous current circuits are in fact integrating ampere-hour meters calibrated in B.O.T. units (§ 114). In alternating current installations integrating watt-hour meters are, however, generally used (§ 115).

Watt-hours divided by 1 000 give kilowatt-hours or 'units' (B.T.U.).

55. **Power in Alternating Current Supply.**—Where the supply is alternating current the product of volts and amperes does not necessarily give the power in the circuit, as the waves of pressure and current may be, and generally are to some extent,

out of phase with one another (§ 11). It is necessary in such cases to multiply the product in volt-amperes by the cosine of the angle ϕ of phase difference (cos ϕ is commonly called the 'power factor'), which, under ordinary circumstances met with in practice, may vary from 0·6 to unity according to the nature of the circuit (§ 157). A suitable wattmeter or watt-hour meter will, however, give correct indications. It is necessary to differentiate here between true power, expressed in kilowatts, and apparent power, expressed in kilo-volt-amperes. This point is discussed in the following paragraphs, and many examples occur in Chapter 14.

56. True and Apparent Power; Power Factor.—Fig. 1, § 11, is a diagram showing the wave form of an alternating electromotive force, and the consequent wave of current in a circuit. In explaining this diagram in §§ 11, 37 it was stated that these two waves do not always coincide, or are not always 'in phase' with one another; consequently the power is not always the product of the pressure and current as shown by a voltmeter and an ammeter. If the instantaneous values of current and pressure be taken at any moment their product will be the power at that moment; but this will be no guide either to the power a fraction of a second later or to its integrated value during the whole period. If in the case of Fig. 1 a single curve is made, on the same scale, to represent the product from moment to moment of the instantaneous values of current and pressure, this resultant curve will evidently represent the actual power at each instant. Now so long as the two waves are both positive, or above the zero line, or both negative, or below it, the algebraic result must be positive and power will be flowing into the circuit; when either wave is on the zero line the power product must for the instant be nil, and the resultant curve must be crossing the zero line also; while for so long as one wave is positive and the other negative the resulting power must be negative (*see also* Fig. 9, § 37)—*i.e.* power is going back momentarily into the generator from the circuit, just as in the single-acting Willans engine the power consumed in compressing air below the piston on the down stroke is delivered back to the crank on the return stroke. The resulting power curve, P, chain-dotted in Fig. 11, is a cosine curve, and it will be found to differ from those of which it is the product, as it will complete one period during each *half* period of the supply; and the areas above and below the datum

line may be equal (Fig. 9, § 37) or may vary until the negative component vanishes (Fig. 8, § 37). The shaded portion of the curve below the datum line represents power momentarily returning to the circuit. The amplitude of the cosine power curve is half the product of the amplitudes of the constituent sine curves; its axis is removed above the axis of the constituents by an amount which is half of the product of the amplitude of the constituents multiplied by the cosine of the angle, ϕ, of their phase difference. In the figure the current is 1 / 12 of a period or 30° out of phase with the E.M.F. (*i.e.* $\phi = 30°$), the maximum value of the current I_m, corresponding to 50 A, and that of the pressure, E_m, to 110 V (instantaneous values). If on these scales the products of the simultaneous values are taken throughout a whole

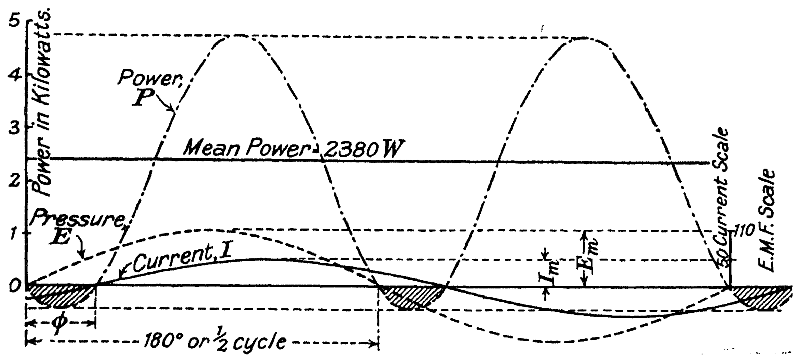


FIG. 11.—Pressure, current, and power curves.

period, the power curve can be plotted from these products as shown. Its amplitude will be $110 \times 50 / 2 = 2\ 750$ and its axis will be at a point $\frac{1}{2} \times 110 \times 50 \times \cos 30° = 2\ 380$ above the principal axis. The maximum instantaneous positive value of the power will be 4 760 W at the peak of the wave. The net power delivered to the circuit will be the *difference* between the areas of the two parts of the curve above and below the zero line.

From this several facts will now be obvious. In the first place, if the waves of current and pressure are exactly coincident in phase (Fig. 8, § 37), the product must always be positive except at the moment it touches zero; the circuit is then said to have a power factor of unity. Secondly, if the waves are in quadrature or 90° out of phase (Fig. 9, § 37), the power put into

the circuit during one quarter-period returns to the generator during the next quarter, so that no power is actually delivered at all, despite the fact that the volts and amperes as shown on the measuring instruments may be at a maximum; the circuit then has a power factor of zero, although the *instantaneous* values of the power, and the consequent mechanical stresses, may be very great. Thirdly, in cases intermediate between these extremes, the actual power is greater or less according to the extent to which the current is out of phase with the pressure, as will be seen if a series of curves is constructed on the above lines; and the power factor varies accordingly. If the waves are out of phase by any particular fraction of a period (expressed as an angle, in degrees, in relation to the cycle of 360°), then the product of the volts and amperes as indicated on the measuring instruments gives the 'apparent power' in volt-amperes or kilo-volt amperes (kVA); and in order to find the true power this product must be multiplied by a number called the 'power factor' (P.F.), which is the cosine of the angle of phase difference, commonly called cos ϕ (*see also* §§ 109-111).* Conversely, to find the apparent power, the true power must be divided by the P.F. In practice the P.F. may be anywhere from 0·5 to unity, though generally in the neighbourhood of 0·8. Non-inductive apparatus, such as glow-lamps, gives a P.F. of unity, *i.e.* the current and pressure are 'in phase' with one another; † in transformers, motors, and other apparatus having an inductive magnetic circuit, the current and pressure are to a greater or less extent 'out of phase,' resulting in a P.F. less than unity, which varies according to the load for the time being. This remark applies also to circuits having capacity (§ 46), except that the current is then in advance of, instead of behind, the E.M.F. This

* Referring to Fig. 10 (§ 44), the power factor of the circuit represented by ABC is: $\cos\phi = AC / CB$ = Resistance / Impedance. If the circuit contains only resistance R and inductance L, the impedance = $\sqrt{[R^2 + (2\pi fL)^2]}$. Then

$$\cos\phi = R / \sqrt{[R^2 + (2\pi fL)^2]} = 1 \Big/ \sqrt{\left[1 + \frac{(2\pi fL)^2}{R^2}\right]},$$

which is sometimes a useful relation.

† It should be noted that the fact that current and pressure waves are in phase is not alone sufficient to make the power factor unity; the waves must also be similar, *i.e.* the resistance must be constant. Even if the inductive effect of the control-magnet coils of an A.C. arc be eliminated, so that the pressure and current waves are in phase, the current wave is distorted by the varying resistance of the arc and the power factor is less than unity (§ 156).

is more fully dealt with in connection with transmission of power (Chapter 14).

Returning to the power curve in Fig. 11, its average value can be proved to be $\frac{1}{2}E_m I_m \cos\phi$ or $110 \times 50 \times 0{\cdot}866 / 2 = 2\,380$ W. That this is so can also be found by using the R.M.S. values instead of the maxima. As shown on instruments, the E.M.F. will be $110 / \sqrt{2} = 77{\cdot}7$ V and the current $50 / \sqrt{2} = 35{\cdot}35$ A. In this particular case the phase difference between E and I is 30° and the P.F. is therefore cos 30° or 0·866, so that the power will be $77{\cdot}7 \times 35{\cdot}35 \times 0{\cdot}866 = 2\,380$ W. This alternative method of consideration amounts to pointing out that $\sqrt{2} \times \sqrt{2} / 2$ = unity.

By way of example, suppose on an alternating current supply there are 50 lamps, taking 100 W each, or 5 kW at 110 V; the current will then be 45·5 A, as the load is non-inductive and the waves of pressure and current will rise and fall together. The P.F. is therefore unity and the consumption will be 5 units per hour. If on the same supply there is a motor, also consuming 5 units an hour, and therefore also taking 5 true kilowatts, but having a P.F. of 0·8, then the *apparent* power taken by the motor will not be 5 kW but 5 / 0·8 or 6·25 kVA. Therefore the current will be 6·25 / 110 or 56·9 A, instead of 45·5, and the wires must be of larger size accordingly. The power factor 0·8 is the cosine of 36°, so this will be the value of ϕ, the angle of phase difference, on the assumption that the waves are sine waves.

The average value of the product of two sine waves 90° out of phase with one another is zero, and this is almost the case with the pressure and current in the primary coil of a transformer on 'open circuit,' *i.e.* with no current flowing in the secondary coil (§ 37). Although the full pressure is on the primary coil, and is causing a current to flow which fully magnetises the iron core on which the coils are wound, the power used is extremely small, *viz.* only what is used in heating up the wires and in magnetising and demagnetising the iron at each cycle (*i.e.* hysteresis, § 34). The balance is returned to the circuit, at each half-cycle, as shown in the shaded part of Fig. 11. If a current is taken from the secondary coil, and increased in amount, the two waves tend to coincide, and the power factor rises; but it never reaches unity in a transformer.

57. Energy Stored in Magnetic and Electrostatic Fields.—The energy stored in a *magnetic field* of density H lines per sq. cm. is $H^2 / 8\pi$ ergs per cu. cm. of the field. A more convenient form of this expression for the case of a solenoid of IT ampere-turns linked with a total flux of Φ lines, is: Energy stored in

magnetic field = $\Phi IT / 20$ ergs = $\frac{1}{2}LI^2 \times 10^7$ ergs, where L = self-induction of coil, in henries. The energy thus stored is expended in a vicious arc at the contacts if an inductive circuit be interrupted suddenly. Another striking example of energy so stored may be seen in the case of a shunt motor; on opening the main switch the kinetic energy of the armature is expended in generating a current which flows through the field coils, and the machine is soon stopped by this 'electrodynamic braking.' If the field winding is relatively powerful or 'heavy,' the energy stored in it will cause the armature to make a few revolutions in the reverse direction after it has come to rest for the first time.

The energy stored in a *condenser* of capacity C farads when charged to a potential difference of V volts is: $\frac{1}{2}CV^2 \times 10^7$ ergs.

The above assumes a constant field or a constant state of charge of the condenser. If the field is produced by a sinusoidal current the energy stored during one quarter-cycle is $\frac{1}{2}LI_m{}^2 \times 10^7$ ergs where I_m = max. value of current. Similarly, if the condenser be charged by sinusoidal E.M.F., the energy stored during one-quarter cycle = $\frac{1}{2}CV_m{}^2 \times 10^7$ ergs, where V_m = max. value of applied pressure.

(1 joule = 10^7 ergs = 0·735 ft.-lb.)

58. Bibliography.—At the end of each chapter in this book there will be found a short list of textbooks which the authors can recommend as being useful for further study. These lists are not offered as being complete, but every effort has been made to present a useful and impartial selection. As regards papers read before institutions and societies, it would be impracticable to give a complete bibliography, and the authors have therefore decided to mention in the bibliographical lists only those papers which have been read before the Institution of Electrical Engineers (London). The *Journal* of the Institution is, or should be, in the possession of most readers of this book. Valuable references to papers and articles in other publications are to be found in *Science Abstracts*.

The books mentioned below deal with broad subjects or give data of more or less general applicability in all branches of electrical engineering. The bibliographies appended to later chapters include publications bearing directly on the subject matter of the respective chapters.

Standards, etc.

Reports of the Committee on Electrical Standards (Cambridge University Press).

Clauses relating to definitions in I.E.E. Wiring Rules (Spon.); H.O. Electricity Regulations for Factories and Workshops; and H.O. Regulations as to Installation and Use of Electricity in Mines (Stationery Office).

B.E.S.A. Reports: *No. 77.*—Electrical Pressures for New Systems and Installations.

No. 108.—Graphical Symbols for Electrical Purposes.

General Electrical Textbooks.

Elementary Lessons in Electricity and Magnetism. S. P. Thompson (Macmillan).

Practical Electricity. W. E. Ayrton and T. Mather (Cassell).

Electricity and Magnetism. R. T. Glazebrook (Cambridge University Press).

Technical Electricity. H. T. Davidge and R. W. Hutchinson (University Press).

Electrical Engineering. A. Thomalen. Translation by G. W. O. Howe (Arnold).

Electrical Engineering. C. V. Christie (McGraw-Hill).

Continuous Current Electrical Engineering. W. T. Maccall (University Tutorial Press).

Theory of Alternating Currents. A. Russell. 2 vols. (Camb. University Press).

Alternating Current Electricity and its Applications to Industry. 2 vols. W. H. Timbie and H. H. Higbie (Wiley).

Electricity: Its Production and Applications. R. E. Neale (Pitman).

Mathematics and Physics.

Mathematics for Engineers. W. N. Rose. 2 vols. (Chapman & Hall).

Metric System for Engineers. C. B. Clapham (Chapman & Hall).

Whittaker's Arithmetic of Electrical Engineering (Pitman).

Arithmetic of Magnetism and Electricity. R. Gunn (Blackie).

Arithmetic of Electrical Measurements. Hobbs (Murby).

Mathematics of Applied Electricity. E. H. Koch (Chapman & Hall).

Textbook of Practical Physics. W. Watson (Longmans).

Pocket Books, etc.

Whittaker's Electrical Engineer's Pocket Book. 5th Edition. Edited by R. E. Neale (Pitman).

Standard Handbook for Electrical Engineers. F. F. Fowle (McGraw-Hill).

American Handbook for Electrical Engineers. H. Pender (Wiley).

Electrical Engineers' Diary (Davis).

Practical Electrician's Pocket Book (Rentell).

Mechanical World Electrical Pocket Book (Emmott).

Kempe's Engineer's Year-book. (Crosby Lockwood).

Mechanical Engineer's Pocket Book. W. Kent (Wiley).

Mechanical Engineer's Pocket Book. D. K. Clark and H. H. P. Powles (Crosby Lockwood).

Whittaker's Mechanical Engineer's Pocket Book (Pitman).

Directories, etc.

Electrician Electrical Trades Directory (Benn Bros.).

Electrician Annual Tables of Electricity Undertakings (Benn).

Universal Electrical Directory (Electrical Review).

Garcke's Manual of Electrical Undertakings (Electrical Press).

Central Station Tables (Rentell).

CHAPTER 2.

MATERIALS.

59. Classification by Conductivity: Conductors and Insulators.—The materials used in electrical engineering may easily and conveniently be divided into the two main groups 'conductors' and 'insulators.' There is no such thing as a perfect insulator, for all substances conduct electricity to a greater or less extent, but the difference in resistivity between 'conductors' and 'insulators' is so enormous that there is no possible ambiguity in this classification. Thus slate, which is a relatively poor insulator, has a specific resistance of about 100 megohms/cm.-cube, whilst that of a high-resistance alloy may be 120 microhms/cm.-cube; the ratio between these values is $8{\cdot}3 \times 10^{11} : 1$. The ratio between the specific resistances of the worst and best conductors is much smaller, *e.g.* the specific resistance of nichrome is 110 microhms/cm.-cube at 0° C., or about seventy times that of copper at the same temperature.

In addition, however, to the main division between conductors and insulators it is convenient to discriminate between good and bad conductors. This may be done by reserving the term 'conductor' for high-conductivity materials such as copper and aluminium or, in general, for materials used where conductivity is desirable and resistance is objectionable; and by applying the term 'resistance materials' to high-resistance alloys and other materials which are used deliberately to dissipate energy, as in motor starters and heating elements. There is no clear boundary between conductors and resistance materials as thus defined. For instance, steel has a sufficiently high resistance to justify its use as a resistance material, yet it is sometimes used as a conductor where great mechanical strength is required. Similarly liquid solutions (electrolytes) of metal salts and acids are necessarily used as conductors in batteries and electrolytic deposition, but they are

used as resistance materials in some types of motor starters and controllers.

Taking the resistance of copper, the principal 'conductor,' as 1·0, that of 'resistance alloys' is from 12 to 70, and that of 'insulators' is many thousands of millions.

Constants of conductors and resistance materials are given in Table 6 (p. 66), and of insulating materials in Table 7 (p. 78).

60. Classification by Other Physical Properties.—Though conductivity and insulation are two of the most important properties of materials used in electrical installations, there are other physical properties which must be considered, *e.g.*:—

(*a*) Mechanical Properties, such as ductility, strength, modulus of elasticity, etc., which determine the applicability of the material from the constructional point of view. These properties have specially to be considered where very fine wires are concerned (*e.g.* lamp filaments); where stresses are severe (*e.g.* in high-speed rotors, transmission line spans, etc.); and where relatively weak material (such as porcelain) used for insulation, is subjected to severe mechanical stress.

The *density* of a material is principally of importance in regard to the estimation of the weights of parts. These factors are useful—

Weight per cu. ft., in lb. = 62·43 × density.
Weight per cu. in., in lb. = 0·036 × density.
Weight per cu. cm., in grm. = density.

(*b*) Thermal Characteristics.—The *temperature coefficient of expansion* of a material is important where exact dimensions have to be maintained (as in certain instruments); where expansion and contraction vary the stresses between points which are fixed mechanically (as in long rigid conductors or transmission line spans); where differences in expansion may crack joints, etc. (as in lamp bulbs, composite insulators, etc.); and in liquids where convection currents contribute to natural cooling (as in oil-immersed transformers). The *specific heat* of a material is important where absorption or storage of heat is concerned, low specific heat being desirable where minimum absorption and rapid heating are required, and high specific heat being desirable for maximum storage of heat. *Thermal conductivity* is important in determining the rating of machinery and the efficiency of furnaces, etc.; it should be high where unavoidable heat losses have to be dissipated as rapidly as possible (*e.g.* through the insulation of machine windings), but it should be low where heat losses have to be reduced (as from electric furnaces). The *melting-point* of a material determines the maximum temperature at which it can be operated in solid form, and this is of practical importance in connection with lamp filaments, refractory bricks, etc., but the limiting temperature at which conductors can be operated is generally the maximum temperature at which their insulation can be operated without deterioration (§ 80).

(*c*) Magnetic Properties.—The magnetic properties of iron and certain special iron alloys (§ 82) are essential to commercial electrical machines and transformers. With the exception of the iron group there are no magnetic

materials of commercial importance. Non-magnetic materials are definitely required where self-induction and magnetic leakage are to be avoided. Unfortunately there is no magnetic insulator; 'non-magnetic' materials are those which have no higher permeability (§ 43) than air.

(*d*) Electrical Properties other than Conductivity.—The conductivity (or resistivity) of a 'conductor' (§ 59) is its only electrical property of practical importance. On the other hand, the resistivity of insulators is relatively unimportant and generally indeterminate (§ 71). The insulation resistance of a winding or network (§§ 4, 281) is generally determined by moisture or by conducting particles; the resistivity of the insulation itself is so high that, in the absence of such foreign influences, break-down occurs by puncture when the electrostatic stress exceeds the *dielectric strength* of the material (§ 72).

The capacity of any condenser increases in direct proportion to the *specific inductive capacity* (§ 46) of the dielectric. The conductors of insulated cables act, with regard to each other and to earth, as the electrodes of condensers in which the insulating material is the dielectric; the higher the specific inductive capacity of the insulating material, the greater the quantity of electricity required to charge the cable and, therefore, the heavier the charging current (§ 311). The different specific inductive capacities of various insulating materials (Table 7) makes it possible to control the potential gradient in a 'graded insulation' (§§ 79, 289).

The reversal of electrostatic stress in any insulation subjected to alternating P.D. involves *dielectric hysteresis* (analogous to magnetic hysteresis, § 34); the energy thus expended in the dielectic heats the latter and may represent an appreciable loss (§ 311).

(*e*) Chemical Properties.—*Purity and homogeneity* are desirable in most electrical materials; for example, small traces of impurity increase greatly the resistance of copper and the conductivity of the cast metal is lower than that of rolled copper. Homogeneity in insulating materials makes for uniformity in dielectric strength; air films are particularly to be avoided (§ 79).

Resistance to moisture and corrosion (*atmospheric or chemical*) is generally a desirable and often an essential characteristic.

According to the relative importance of the above-mentioned properties in individual applications, electrical materials can be classified in any number of groups. For our purpose, it is convenient to adopt the general classification: Conductors, resistance materials, insulating materials, magnetic and non-magnetic materials, and refractories. Data bearing on other characteristics are given where of special interest.

61. Temperature Coefficient of Resistance.—The specific resistance (§ 18) of any material is a constant for any specified temperature, but varies with temperature. The resistance of copper and most other conductors increases with temperature, *i.e.* the temperature coefficient of resistance is positive. Constantan and other useful alloys have practically constant resistance within wide limits of temperature, *i.e.* they have zero (or

nearly zero) temperature coefficient of resistance. The resistance of carbon, of electrolytes, and of india-rubber and other dielectrics (§ 71) decreases as the temperature rises, *i.e.* the temperature coefficient of resistance is negative. The positive temperature coefficient of, say, iron may be used to compensate for the negative coefficient of the electrolyte in electrolytic ampere-hour meters (§ 114).

In general, the resistance of a conductor varies with temperature according to the law

$$R_t = R_0 (1 + at) \quad . \quad . \quad . \quad . \quad (1)$$

where R_t, R_0 are the resistances at temperatures $t°$ and 0° C. and a is the *temperature coefficient of resistance* per 1° C.* This simple relation holds good only for a limited range of temperature, say 100° C. The resistance at temperature t is expressed in terms of the resistance at 0° C. If the resistance be R'_t at some other temperature t' we have: $R'_t = R_0 (1 + at')$. Dividing this equation by equation (1), we have—

$$\frac{R_t'}{R_t} = \frac{1 + at'}{1 + at} = 1 + \frac{a(t' - t)}{1 + at},$$

whence . $$R_t' = R_t\left[1 + \frac{a}{1 + at} \cdot (t' - t)\right].$$

This means that the resistance at a temperature t' can be calculated directly from the resistance at a temperature t (without reference to the resistance at 0° C.), by using the formula—

$$R_t' = R_t[1 + \beta(t' - t)] \quad . \quad . \quad . \quad . \quad (2)$$

in which $$\beta = a/(1 + at) = 1\Big/\left(\frac{1}{a} + t\right).$$

In other words, if a be the temperature coefficient of resistance for equation (1), which is based on resistance at 0° C., then β is the temperature coefficient of resistance for equation (2), in which the basic resistance is that at $t°$ C.

For copper, $a = 0{\cdot}004\,265$ at 0° C.; and $\beta = 1 / (234{\cdot}5 + t) = 1 / (234{\cdot}5 + 20) = 0{\cdot}003\,93$ at 20° C. If the resistance R_{20} at 20° C. be known we could calculate the resistance R_0 at 0° C. from: $R_{20} = R_0 (1 + {\cdot}004\,265 \times 20) = 1{\cdot}085\,3\ R_0$; and the resistance R_{30} at 30° C. from: $R_{30} = R_0 (1 + {\cdot}004\,265 \times 30) = 1{\cdot}128\ R_0$, but it is simpler to work from: $R_{30} = R_{20} (1 + {\cdot}003\,93 \times 10) = 1{\cdot}039\,3\ R_{20}$. The result obtained is the same by both methods.

* The temperature coefficient per 1° F. = $\frac{5}{9}$ × the coefficient per 1° C.

The variation of resistance of a conductor with temperature may be utilised to determine the temperature of the conductor (§ 122).

CONDUCTOR MATERIALS (*see* Table 6, p. 66).

62. Copper.—Copper is by far the most extensively used electrical conductor, combining, as it does, high electrical conductivity with excellent mechanical properties and relative immunity from oxidation and corrosion under service conditions. Electrolytic copper is practically pure. The smallest traces of impurities increase enormously the resistance of the metal. Hard drawn wire is used for overhead conductors (§ 307), due to its superior tensile strength; for most other purposes the softer, annealed wire (§ 280) is used, this having 2 or 3 °/ₒ lower resistance. Rolled bars are used where large sections are concerned. Copper castings are liable to be unsound. Copper gauze brushes are still used on low voltage, heavy current dynamos for electroplating, etc.*

The *international standard of resistance for copper*, as laid down by I.E.C. Publication No. 28, is based on the following values:—

Standard Annealed Copper at 20° *C.* (68° *F.*).

(i) Resistance of a wire 1 metre long and of uniform section 1 sq. mm. = $1/58\ \Omega = 0{\cdot}017\,241\ \Omega$ (= *volume resistivity*, § 18).

(ii) Density, 8·89 grm. per cu. cm.

(iii) 'Constant mass' temperature coefficient of resistance, 0·003 93 per degree Centigrade.

(iv) Resistance of uniform wire 1 metre long, weighing 1 grm. = $0{\cdot}153\,28\ \Omega$ (= *mass resistivity*, § 18).

It is stipulated that the *conductivity of commercial annealed copper* be expressed as a percentage, at 20° C., of that of standard annealed copper. The temperature t° C., at which measurements are made, must be within ± 10° C. of 20° C., *i.e.* between 10° C. and 30° C. Then if R be the resistance at t° C. of a copper wire L metres long weighing m grm., the *percentage conductivity of the copper* is—

$$100 \times \frac{0{\cdot}153\,28}{(Rm/l^2) + 0{\cdot}000\,6\,(20 - t)} \quad . \quad . \quad \text{(I)}$$

* Sparking and wear on the commutator may be reduced by soaking the brushes periodically in a mixture of vaseline and finest graphite; this treatment is permissible only for low voltage machines (10-15 V).

Data, consistent with those above, adopted by the B.E.S.A., are as follows:—

Standard Annealed Copper at 60° *F.* (15·6° *C.*).

Weight = 555·11 lbs. per cu. ft.

Specific gravity = 8·892.

$$\text{Weight per yard} = \frac{\text{area in sq. in.}}{0\cdot 000\,012\,352\,75}\ \text{grains.}$$

$$= 11\cdot 564 \times (\text{area in sq. in.})\ \text{lbs., approx.}$$

$$\text{Resistance per yard (annealed)} = \frac{0\cdot 000\,024\,007\,9}{\text{area in sq. in}}\ \Omega.$$

$$\text{,,} \qquad \text{,,} \quad \text{(hard-drawn)} = \frac{0\cdot 000\,024\,728}{\text{area in sq. in.}}\ \Omega\text{, approx.}$$

Resistance per 1 000 yds. (annealed) = n / W Ω; where

W = weight of wire in grains per yard; and

n = 1 943 for plain standard annealed copper

= 1 982 for tinned wire from 0·007 in. to 0·036 in. dia. inclusive

= 1 962 for tinned wire exceeding 0·036 in. dia.

Coefficient of linear expansion = 0·000 009 44 per 1° F.

= 0·000 017 per 1° C.

The *temperature coefficient of resistance* of standard annealed copper is 0·004 26 at 0° C. and 0·003 93 at 20° C. (§ 61).* The coefficient decreases with the percentage conductivity of the copper (as expressed at (I) above); down to 90 °/ₒ conductivity the temperature coefficient of resistance of copper of p °/ₒ conductivity may be taken as $(p / 100) \times$ the temperature coefficient of standard annealed copper at the same temperature.

B. Welbourn † gives the following values for the *modulus of elasticity of hard-drawn copper strands*:—

20 000 000	lbs.	per sq. in.	for	7-strand	cable.
17 500 000	,,	,,	,,	19-	,,	,,
15 500 000	,,	,,	,,	37-	,,	,,

63. Aluminium.—Aluminium is often used in place of copper for bus-bars and overhead transmission lines and, less frequently, for insulated cables and windings. It is much lighter than copper (the ratio of the densities being 1 : 3·42), and its electrical conductivity and mechanical strength are lower than those of

* For a temperature rise of 50° C., which is not uncommon in practice the resistance at 0° C. must be multiplied by 1 + (50 × 0·004 26) = 1·213. This shows the futility of expressing commercial electrical quantities to within 1 in 1 000; only when all relevant conditions are stated can there be any justification for such expression.

† *Jour. I.E.E.*, Vol. 56, p. 53.

copper in about equal ratios, so that, for equal electrical conductivities, aluminium and copper conductors are of nearly equal strength. The wind pressure and weight of snow are, however, greater on an aluminium line than on a copper line of equal conductivity because (the specific conductivity of aluminium being about 61 % that of copper), the aluminium line is of 65 % greater cross-section and 28 % greater diameter than the equivalent copper line. The relative weight of electrically equivalent conductors is aluminium 0·48, copper 1·0, so that the bare metals are about equally economical when the price of aluminium is 2·08 times that of copper. Additional information on the use of aluminium for overhead lines is given in §§ 308, 331.

The larger diameter of the conductor renders insulated aluminium cables much more costly than copper cables of equal conductivity; on the other hand, the larger diameter with aluminium reduces dielectric stress and corona loss at the surface of high-voltage conductors.

Aluminium was used instead of copper in the armature and field windings of motors, generators, etc., and in transformers built in Germany during the Great War, and it has been claimed that such machines compete in efficiency and price with copper-wound machines. Aluminium is, however, at an obvious disadvantage wherever the space for windings is limited.

The thin film of oxide which forms on the surface of aluminium makes soldering a matter of some difficulty and uncertainty. Mechanical joints (bolts, clamps, twisted sleeves, etc.) are used extensively, and welded joints have been used in aluminium windings. (*See also* § 383.)

The use of aluminium in lightning arresters and rectifiers is mentioned in § 346 and Chapter 17.

64. Iron and Steel as Conductors.—The magnetic properties of iron and steel are discussed in §§ 81-84. The resistivity of steel is about six or eight times that of copper, so that steel is used as a conductor only when: (i) mechanical strength is specially important; or (ii) so large a cross-section is required, for other reasons than for conductivity, that steel is more economical than copper (§ 309).

(i) All steel and steel-cored copper or aluminium-stranded wires are used for very long spans in *overhead lines* (§§ 309, 331), and tinned or galvanised small

steel wires are often used with copper for strength in *small flexible wires and cables*.

(ii) Low-carbon steel is used for *conductor-rails* in traction circuits (Chapter 35). The British Standard method of specifying the resistance of such rails (B.E.S.A. Report No. 68) is to state the resistance in microhms at 60° F. (15·6° C.) of a rail of the same material as the conductor rail in question, having a length of 1 yd. and a weight of 100 lbs. As thus specified, the resistance of flat-bottom conductor rails now in use ranges from 15 to 19·5 microhms (mean 18 microhms) per 100-lbs. yard; whilst that of specially hard T rails ranges from 19·8 to 20·5 microhms (mean 20·2 microhms) per 100-lbs. yard. For chemical analyses, and conversion formulæ and tables reference should be made to B.E.S.A. Report No. 68.

Iron pipes are sometimes used as *bus-bars*, and steel is fairly satisfactory for *slip rings*.

Iron wires, used in Germany during the war to replace copper, have been proposed for normal use in *small domestic installations* where the section of copper required for mechanical strength is greater than would be needed for conductivity alone. It is possible that stainless iron or steel may find an application in this field. Galvanised iron wire has, for a similar reason, been found economical in *overhead lines* supplying small rural loads (§ 331.)

Wherever iron or steel is used as a conductor the possible importance of skin-effect (§§ 38, 309) should be considered.

The specific resistance of *grey cast iron* is roughly ten times that of steel and seventy times that of copper; for this reason, no reliance should be placed upon the metal of a cast-iron joint box for carrying appreciable current.

Apart from the increase in resistance due to temperature coefficient (§ 61 and Table 6, p. 66), the resistance of iron increases greatly and suddenly at the temperature of recalescence (about 680° C.). This phenomenon is utilised in the ballast resistance of the Nernst lamp to compensate for the unstable pressure-current characteristic of the filament itself. It is also employed in other applications as an automatic current regulator, the principle being that the iron wire (enclosed in a hydrogen-filled bulb) is brought nearly to red heat by the normal current of the circuit; an increase of current then brings the iron to the temperature of recalescence, greatly increases its resistance, and thus limits the increase of current.

65. Other Metallic Conductors.—The notes on these are necessarily brief and, for convenient reference, the metals are arranged alphabetically.

Bismuth.—When bismuth is placed in a magnetic field, the electrical resistance of the metal increases, nearly in proportion to the field strength. A spiral

coil of bismuth wire wound non-inductively, calibrated by reference to a magnetic standard, and used in conjunction with a Wheatstone bridge, is sometimes used to measure field strengths (§ 121). It is unsuitable for alternating fields due to time lag in the changes of resistance.

Brass for casting generally contains 66 % copper and 34 % zinc. Sound castings are obtained more easily than in copper. The alloy is cheaper than copper and is used for various current-carrying parts in which the cross-section is determined by mechanical rather than electrical considerations.

Bronze.—Silicon bronze and phosphor bronze wires are used for long spans in overhead conductors (§ 331). Silicon bronze consists of copper and up to 5 % of silicon, and a typical phosphor bronze contains Cu, 92·5; Sn, 7; P, 0·5. Constants for both types of bronze are given in Table 49, § 331.

Cadmium-copper.—Alloys containing up to 1·1 % cadmium give wires which are stiffer, harder, and of higher tensile strength than hard-drawn copper (Table 49, § 331). The annealing temperature is raised, 1·1 % cadmium wires softening only slightly at 260° C.

Lead.—This metal is used for sheathing various types of insulated wires and cables, particularly where moisture is to be excluded. The addition of about 3 % tin increases the tensile strength 50 %. Lead is also used in bimetal fuse wire and for interconnecting the plates and cells of accumulator batteries.

Mercury.—This metal is made the basis of the international definition of the ohm (§ 3). It is used for making and breaking contact in many types of apparatus, but is suitable only for weak currents and low voltages, and should be used *in vacuo* or protected from air by a layer of oil to avoid oxidation. The use of mercury in lamps and rectifiers is mentioned in Chapters 25 and 17 respectively.

Nickel is malleable and resists corrosion. It is used for connections in heat ing and cooking apparatus, for supports in glow lamps, and for sparking plug electrodes. It is a constituent of many important resistance-alloys (§ 67).

Nickel Steels offer a wide range of valuable properties. High-tensile steels (3 % Ni) are used for large dynamo frames and high-speed rotors. For sparking-plug electrodes 22 % Ni steel is suitable. The 25 % Ni steel is non-magnetic (§ 84). Invar is 36 % Ni steel and has practically zero temperature coefficient of expansion. As a substitute for platinum leading-in wires for lamps, etc., there is used platinite (46 % Ni steel) or a 38 % Ni steel wire copper-coated.

Platinum was formerly used for the leading-in wires of glow lamps and for contact pieces, but its price has become prohibitive; *see* Nickel Steels and Tungsten.

Selenium.—When suitably annealed, selenium assumes a crystalline form, and has then the curious property that its electrical conductivity varies (roughly) as the square root of the intensity of illumination upon the specimen. Different workers advise different methods of preparing the material, and quote widely different values for the electrical resistance, light sensitivity, and time lag in response. The conductivity may increase 100-200 times or more when the material is taken from a dark room into sunlight; some specimens increase in resistance when taken from dark to light, but the change in resistance of such 'light negative' material is generally very small. The time lag in the changes of resistance under varying illumination may be reduced by suitable treatment of the material, and selenium cells are used to control flashing buoys, and in the electrical transmission of pictures; also in devices for enabling the blind to read by sound, and in the recording and reproduction of sound for 'talking (cinema) pictures.'

It is reported (*El. Rev.*, Vol. 89, p. 717) that synthetic antimonite may be used as a substitute for selenium, it having no appreciable lag in responding to variations in light.

Silver has higher conductivity than copper, but is too costly for general use. It is used for special contacts unless a more refractory metal is required, *e.g.* platinum or tungsten.

Tin is used for fuses (§ 342) and to prevent mutually injurious action between rubber and copper (§ 282). At joints, tin prevents corrosion and helps to ensure good contact, whether by soldering or clamping.

Tungsten is now the standard material for the filaments of glow lamps (Chapter 25) and thermionic valves (Chapter 17), and is used for sparking points and contact pieces. Its *refractory nature makes the manufacture of the metal* difficult. The ore is reduced to tungsten powder which is compressed into blocks, and sintered by the passage of a heavy current. By swaging, rolling, and repeated drawing the sintered rods can be reduced to wire of 1 mil diameter. The initial stages of mechanical working have to be conducted at temperatures between 1 000° and 1 500° C., but as working proceeds the ductility increases and the temperature may be reduced. The tensile strength of drawn tungsten wire from 1 to 5 mils in diameter is from 290 to 200 tons per sq. in.

Tungsten steels are used for permanent magnets (§ 83).

Zinc is used to galvanise steel cores and armouring wires as a protection against rusting. It was used in place of copper in windings and cables in Germany during the war, but was found difficult to handle due to its brittleness. The electrical conductivity is less than half that of aluminium and little more than one-fourth that of copper.

66. Carbon and Graphite.—Carbon is used for electrical purposes in its amorphous form (lampblack, charcoal, gas-retort carbon, petroleum-coke, etc.; sp. gr. 1·6 to 2·0) and in its crystalline form (graphite, sp. gr. 2·3). One or more varieties of the amorphous form are ground finely, mixed with tar or pitch as binder, moulded under pressure and baked out of contact with air in order to obtain dense and strong amorphous carbon for use as electrodes in *arc lamps* or *electric furnaces.* By heat treatment in an electric furnace, the electrodes may be 'graphitised.'

Carbon brushes for electrical machinery are made by a similar process; the principal types are as follows:—

Amorphous carbon brushes, to which a small percentage of graphite is sometimes added to reduce friction, are generally hard enough to wear the micas level with the commutator bars, and are therefore suitable where micas are not 'under-cut.' The coefficient of friction is usually between 0·22 and 0·28; the permissible current density 35 to 40 A per sq. in.; and the specific resistance 1 500 to 2 500 microhms per in.-cube.

Graphitised brushes are made from a mixture containing more or less graphite, and the amorphous carbon is converted to the graphitic form by heating in an electric furnace. These brushes are relatively soft and it may be necessary to under-cut the micas. The coefficient of friction is usually between 0·20 and 0·25,

TABLE 6.—*Approximate Constants of Electrical Conductors and Resistance Materials. (Compiled from Various Sources.)*

CONVERSION FACTORS.

Resistance per in.-cube = 0·394 × resistance per cm.-cube.
Ohms per mil.-ft. = 6·02 × microhms per cm.-cube.
Temperature coefficient per 1° F. = $\frac{5}{9}$ × temperature coefficient per 1° C.
Temperature in °F. = (°C × $\frac{9}{5}$) + 32°.

Material.	Composition, State, etc. For key see Note at foot of Table.	Specific Gravity.	Specific Resistance Microhms Per cm.-cube at 20° C.	Temperature Coefficient of Resistance Per 1° C.	Tensile Strength. Tons / Sq. In.	Modulus of Elasticity Million Lbs. per Sq. In.	Temperature Coefficient of Linear Expansion Per 1° C.	Melting-Point °C.	Specific Heat 0°-100° C.	*See also* §
Aluminium	Cast soft	2·68	2·8	0· 003 5	—	—	0· 000 024	655	0·212	63, 308, 331
,,	Rolled or drawn	2·71	2·9	0· 003 5	11½-15	9·8				
Antimony	—	6·6	40·0	—	—	—	—	630	0·051	—
Bismuth	—	9·8	116·0	0· 004 2	—	—	—	269	0·030	65
Cadmium	—	8·6	10·8	0· 004 2	—	—	—	—	—	65
Carbon	Graphite	1·9-2·3	400-1 200	*minus* 0· 000 6- to 0· 001 2	—	—	—	3 450	0·19-0·20	66
,,	Moulded electrodes	1·5-2·0	3 500-7 500							
Cobalt	—	8·7	10·4	0· 003 3	—	—	—	1 485	—	82, 83
Copper	Annealed	8·89	1·72	0· 003 9	14	—	0· 000 017	1 091	0·094	62, 307, 331
,,	Hard drawn	8·93	1·77	0· 003 9	21-30	15-16				
Gold	—	19·3	2·47	0· 003 8	17	13·7	0· 000 014	1 063	0·031	—
Iridium	—	22·4	5·3	—	—	—	—	2 290	0·032	122
Iron, pure	(*See also* cast iron and steel)	7·8	9-10	0· 006 2	30-40	26·3	0· 000 012	1 500-1 530	0·116	64, 81
Lead	—	11·4	21·0	0· 004 1	1¼	2·5	0· 000 030	327	0·030	65
Magnesium	—	1·7	4·4	0· 003 8	—	—	0· 000 032	632	0·246	67
Mercury	—	13·6	96·0	0· 000 9	—	—	—	− 38·8	0·033	65
Molybdenum	—	8·5	4·5	0· 005	—	—	—	2 500	—	—
Nickel	Commercial	8·85	10·5	0· 004	35	29·3	0· 000 013	1 450	0·109	65, 67
Palladium	—	—	10·9	0· 003 5	—	—	—	—	—	—
Platinum	—	21·5	11·8	0· 003 8	21	24	0· 000 009	1 710	0·032	65, 122
Silver	—	10·5	1·6	0· 004	19	9·8	0· 000 019	960	0·056	65

TABLE 6 (*continued*).

Tantalum	—	16·6	15·0		0· 003 3	$27\frac{1}{2}$	—	0· 000 007	2 910	0·036	—
Thallium	—	11·9	19·0		0· 004	—	—	—	301	0·033	—
Tin	—	7·3	11·5		0· 004 6	2	6·8	0· 000 022	232	0·055	65
Tungsten	—	18·8	4·7-5·0 annealed 5·8-6·2 drawn		0· 005	200-290 wires 5 to 1 mil. dia.	—	0· 000 004	3 300	0·034	65
Zinc	—	7·2	6·2		0· 004	10-13	12·3	0· 000 029	419	0·095	65
Zirconium	—	4·2	4·2		0· 005	—	—	—	1 700	—	—
Cast iron	'No-Mag' (1*a*)	—	140		0· 000 9	—	—	—	—	—	84
,, ,,	Ordinary	7·2	75-100		0· 001 9	5-13	—	—	—	—	64
,, ,,	Malleable	—	23-33		—	—	—	—	—	—	—
Manganese steel	1·0-1·3 % C ; 11-13 % Mn	7·85	70		0· 001 4	65	—	0· 000 018	—	—	84
Silicon steel	$3\frac{1}{2}$ % Si	7·7	50-60		—	30-35	—	—	—	—	331
Nickel steel	$4\frac{1}{2}$ % Ni	—	30		—	39	28·5	—	—	—	—
Carbon steel	Conductor rails, etc. ; up to 0·4 % carbon	7·8	10-14		0· 004-0· 005	30-60	29·5	0· 000 012	1 350	—	64
,, ,,	High carbon	—	15-45		0· 002-0· 004	55-100	—	0· 000 010	—	—	64, 309, 331
				At °C.							
Nichrome II	(3*d*)	8·02	110	24	0· 000 16	—	—	—	—	—	—
Calido	Ni—Cr—Fe (2*b*)	8·15	103	—	0· 000 36	—	—	—	1 530	—	—
Manganese-copper	30Mn + 70Cu	—	101	—	0· 000 04	—	—	—	—	—	—
No. 525 nickel-chrome	(3*c*)	8·15	100	24	0· 000 37	—	—	—	—	—	—
Nichrome	Ni—Cr—Fe (3*b*)	8·15	100	24	0· 000 44	—	—	—	1 538	—	—
Rayo	Ni—Cr—Fe (2*d*)	8·05	95·7	—	0· 000 18	—	—	—	1 530	—	—
Kromore	(3*b*) nickel-chromium alloys	8·9	95	24	0· 000 18	—	—	—	—	—	—
Chronic	(4*b*) nickel-chromium alloys	8·28	93·5	15	0· 000 42	47	—	—	1 400	—	—
Comet	(2*ce*) nickel-chromium alloys	8·15	87	—	0· 000 7	—	—	—	1 510	—	—
Superior	Nickel-steel	8·1-8·2	87	—	0· 000 8	—	—	—	—	0·117	—

TABLE 6 (*continued*).

Material.	Composition, State, etc. For key see Note at foot of Table.	Specific Gravity.	Specific Resistance Microhms Per cm.-cube. At 20° C.	At °C.	Temperature Coefficient of Resistance Per 1° C.	Tensile Strength. Tons / Sq. In.	Modulus of Elasticity. Million Lbs. per Sq. In.	Temperature Coefficient of Linear Expansion Per 1° C.	Melting-Point °C.	Specific Heat 0°-100° C.	*See also* §
No. 193 alloy	Nickel steel (3*c*)	8·14	87	24	0· 000 72	—	—	—	—	—	—
Climax	(5)	—	87	—	0· 000 54	—	—	—	—	—	—
Beacon	(6)	8·13	85	—	0· 000 7	—	—	—	—	—	—
Ferrozoid	Nickel steel (4*c*)	8·28	84	15	0· 000 76	42·4	—	0· 000 007	1 490	—	—
Kruppin	,, ,,	8·10	84	15	0· 000 63	—	—	—	—	0·012 (?)	—
Phenix	,, ,, (2*c*)	8·10	83	—	0· 001 1	—	—	—	1 510	—	—
Rheostene ; Resista	—	—	69	—	0· 001 04	—	—	—	—	—	—
SB alloy	(5)	—	53	—	—	—	—	—	—	—	—
Ferno	(6)	8·88	50	—	near nil	—	—	—	—	—	—
Constantan ; Eureka	40-45 % Ni ; 60-55 % Cu (*efgh*)	8·88	49	15	0· 000 01	—	—	—	—	0·095-0·105	—
Advance	Ni—Cu (3*g*)	8·9	49	24	0· 000 018	—	—	—	—	—	—
Ideal	Ni—Cu (2*efg*)	8·9	49	15	0· 000 005	—	—	—	1 210	—	—
Hecnum	— (7)	—	48	—	0· 000 041	61-66	—	—	over 1 260	—	—
Ferry	Ni—Cu (4*cf*)	8·99	47·2	15	0· 000 022	39	—	0· 000 014 6	1 250	—	—
Therlo	Cu—Mn—Al (3*j*)	8·15	46·7	24	0· 000 006	—	—	—	—	—	—
Lucero	Ni—Cu (2*c*)	8·9	46·5	—	0· 000 7	—	—	—	1 350	—	—
Rheotan	—	8·5	45	—	0· 000 41	—	—	—	—	0·093	—
Nickelin	63Cu ; 32Ni	8·2-9·5	43	—	—	—	—	—	—	0·08-0·10	—
Monel metal	67Ni ; 28Cu ; 5Fe, etc. (*k*)	—	42	15	0· 001 9	—	26	—	1 370	—	—
Tarnac ; Manganin	84-55Cu ; 4-41Ni ; 12-1Mn (4*fl*)	8·9-8·5	40-50	15	0· 000 02-0· 000 04	—	—	—	910	0·097-0·105	—
BB alloy	Nickel silver (4)	8·98	40·2	15	0· 000 21	34·8	—	0· 000 015 7	—	—	—
Zodiac	,, ,, (4*f*)	8·97	36	15	0· 000 23	37·8	—	0· 000 015 9	—	—	—
German silver	60Cu ; 15Ni ; 25Zn (*g*)	8·5	20-35	15	0· 000 3-0· 000 6	30	—	—	—	0·094-0·096	—
Argentan	—	—	28·7	15	0· 000 39	—	—	—	—	—	—
Platinoid	German silver + 0·1 % W	9·0	35-45	15	0· 000 23	—	—	—	—	—	—
Ferro-nickel	—	—	27-36	24	0· 002 2	—	—	—	—	—	—

Table 6 (*continued*).

Nickel-silver	52-80Cu ; 10-35Zn ; 5-30Ni (4)	8·93-8·8	29-18	15	0· 000 27-0· 000 76	30-29½	—	0· 000 016-0· 000 018	—	—	—
Platinum-silver	66-33 % Pt (*m*)	Up to 17·8	29·25	15	0· 000 31-0· 000 33	—	—	—	—	—	—
Cupro-nickel	(4*c*)	8·88	26·4	15	0· 000 285	23	—	—	—	—	—
Platinum-rhodium	90Pt ; 10Rh (*e*)	20·6	21·3	15	0· 001 5	—	—	—	—	—	—
Edina	(6)	7·8	21	—	0· 009	—	—	—	—	—	—
Magno-nickel	Ni—Mn (2*k*)	8·8	20	—	0· 002	—	—	—	1 400	—	—
Platinum-iridium	80Pt ; 20Ir (*em*)	—	32·5	15	0· 002	—	—	—	—	—	—
Bronze	88Cu ; 12Sn	8·7	17·7	15	0· 002	40	17·5	—	—	0·09 (ca.)	—
Aluminium bronze	97Cu ; 3Al	—	8·97	15	– 0· 000 5	—	—	—	—	—	—
Phosphor bronze	92½Cu ; 7Sn ; 0·5P	8·7-8·9	7-8	—	0· 000 9	20-65	15	0· 000 018	—	—	331
Brass	66-90Cu ; 34-10Zn	8·4-8·7	7-3½	15	0· 002-0· 004	10-24	13·7	0· 000 019	—	0·092	—
Silicon bronze	—	—	3·9-1·8	—	0· 001 5-0· 002	49-28	—	0· 000 018	—	—	331

Note.—The data concerning proprietary materials are mainly as given by the makers (or calculated therefrom). The *reference numbers* in the Table apply to the subjoined list of makers or suppliers, and the *reference letters* to the list of typical applications for the various materials.

(1) Ferranti, Ltd., Hollinwood.
(2) Electrical Alloy Co., U.S.A.
(3) Driver, Drennan & Cooper, Ltd., Manchester.
(4) H. Wiggin & Co., Ltd., Birmingham.
(5) Driver Harris Wire Co., U.S.A.
(6) Bruntons, Musselburgh.
(7) A. E. Heckford, Birmingham.

(*a*) Switch or transformer covers, cable boxes, resistance grids, etc.
(*b*) Heating elements and rheostats for high temperatures.
(*c*) Resistances to be worked up to about 250° C.
(*d*) Permanent working at 1 000°-1 100° C.
(*e*) Thermo-couples.
(*f*) Shunts ; and resistances to 'swamp' the temperature coefficient of copper, etc.
(*g*) Resistances to be worked near atmospheric temperature.
(*h*) Thermo-E.M.F. against copper 0· 004 6 V per 100° C.
(*j*) ,, ,, ,, ,, 0·3 microvolt per 1° C.
(*k*) Contact points, sparking plug electrodes, etc.
(*l*) Thermo-E.M.F. against copper 2 to 2½ microvolts per 1° C.
(*m*) Hot wires of measuring instruments.

the permissible current density 55 to 60 A per sq. in.; and the specific resistance 600 to 1 200 microhms per in.-cube.

Graphite brushes, made from graphite with a small proportion of binder, are very soft and should be used with under-cut micas. The coefficient of friction is low, from 0·12 to 0·17; the permissible current density from 60 to 65 A per sq. in.; and the specific resistance from 600 to 1 000 microhms per in.-cube.

Metal-graphite brushes contain a proportion of powdered metal (generally copper) which increases the conductivity. This type of brush is suitable only for slip rings or low-voltage commutators (up to 100 V). The coefficient of friction is from 0·18 to 0·20; and the permissible current density is from 60 to 100 A per sq. in. on commutators (50 °/₀ higher on slip rings), according to the proportion of metal in the brush. For electroplating dynamos (up to 10 or 12 V) metal-graphite brushes are available with specific resistance as low as 7 microhms per in.-cube; other brushes, containing less copper, range from 100 to 500 microhms per in.-cube.

Other uses of carbon are for glow lamp filaments, arcing tips, and rheostats. *Carbon filament glow lamps* are still used where their energy consumption is of secondary importance or where (as in radiator lamps) it is actually requisite. *Carbon arcing tips* are used to break circuit in switchgear, because they are damaged but slightly by arcing and are easily renewed (§ 365). The critical voltage required to maintain an arc between carbon electrodes is higher than that required between metal electrodes (say 35-40 V compared with 12-15 V). For this reason, and because of its very high melting-point, and the relatively low electrical conductivity of the carbon arc (compared with the metallic arc), carbon is more effective than metals as a material for the arcing contacts of switchgear, provided that its mechanical weakness does not prevent its being used. Carbon powder, granules, and plates are used for *rheostats* of various types; the resistance being variable within wide limits by changing the mechanical pressure applied to the material. A line drawn with a 'lead' pencil on a piece of ground glass can be used as a high resistance (of the megohm order).

Carbon differs from most metallic conductors in that it has a *negative temperature coefficient of resistance* (Table 6). Except where carbon is used as a resistance material, this negative temperature coefficient is advantageous; for instance, the resistance of carbon-furnace electrodes may be 50 °/₀ lower at the working temperature than at atmospheric temperature.

67. Resistance Materials.—Conductors of high resistance are used where it is actually desired to dissipate electrical energy as eat, *e.g.* in starting and regulating apparatus for motors (Chapter

29), in heating and cooking apparatus (Chapter 26), and so forth. In such cases it is usual to speak of the high-resistance conductors as 'resistances,' and to say that they are used as 'resistance coils,' 'resistance elements,' or 'heating elements.'

The British Standard specification for metallic resistance materials (B.E.S.A. Report, No. 115) divides these materials into five classes :—

(A) For use when a low temperature coefficient is required at temperatures not exceeding 60° C. (as in standard resistances and sub-standard instruments). The permissible temperature coefficient is ± 0· 000 02 per 1° C., within the range 10° to 60° C.

(B) For use when the temperature coefficient may vary more than in Class (A) and at temperatures not exceeding 200° C. (as in instruments other than sub-standard). The permissible temperature coefficient is ± 0· 000 04 per 1° C. within the range 10° to 100° C.

(C) For use when the temperature coefficient may vary over a wide range and at temperatures not exceeding 300° C.

(D) For use at high temperatures not exceeding 700° C. (as in heating apparatus).

(E) For use at high temperatures not exceeding 1 000° C. (as in heating apparatus).

In classes (C), (D), (E) the temperature coefficient is to be stated by the supplier who must also declare, for all classes, the thermal E.M.F. of the material against copper at 0° and 100° C.

The resistance, R, of any conductor is given by: $R = \rho l/A$ (§ 18). The specific resistance, ρ, is a constant of the material employed, but any number of values can be given to the length, l, and cross-section, A, of the conductor to obtain the desired value for R. The resistance must be designed with reference to the current to be carried, for the energy dissipated as heat is I^2R watts (§ 49), and this causes a temperature rise which is greater the smaller the radiating surface of the wire. Though the total resistance required may be the same, it is necessary to use a larger wire or strip for a heavier current and a greater length is then required to provide the desired resistance. It does not follow that material of higher specific resistance is better than one of lower specific resistance for a particular purpose. The amount of energy to be dissipated and the permissible temperature rise may be such that it is more convenient or more economical to use the material of lower specific resistance. Tables of current-carrying capacity for wires of various materials and sizes, for specified temperature-rises, are applicable only to a particular set of cooling facilities.

In practice, it is generally necessary to find by experiment the best material, dimensions, and arrangement of resistances, for the purpose concerned.

As shown by Table 6, *nickel* is an ingredient of many important resistance materials; alloyed with chromium it furnishes wires which can be operated indefinitely at red heat in air without becoming brittle or seriously oxidised. Backer * claims to have discovered a *magnesium alloy* suitable for use in heating apparatus and electrical machinery when insulated only by an oxide film produced by boiling the metal in water.

Glow lamps are sometimes used as resistances, particularly when charging small accumulators from lighting supply.

Mixtures of *carbon dust and carborundum* and prepared blocks of similar composition are used between lightning arresters and earth, and between generator neutrals and earth to limit the current flowing (§§ 346, 354).

Silit consists of a mixture of silicon carbide and silicon, or of silicon carbide alone (*see also* carborundum, § 85). It has been used considerably on the Continent for electric heating elements. The material is supplied in the form of tubes or rods and can be turned or cut to shape. The resistance at 1 000° C. is said to be about one-third of that at atmospheric temperature, but to be nearly constant between 1 000 and 1 400° C. Silit is unaffected by heating to 1 400° C. in air.

Liquid resistances are discussed in § 68 and Chapter 29.

68. Electrolytes.—Electrolytes are conductors of electricity which are chemically decomposed by the passage of direct current †; generally they are liquids (as in primary and secondary batteries (§ 127 and Chapter 18), and electroplating vats, etc. (Chapter 38), but, at high temperatures, electrolytic conduction and decomposition occur in many refractory materials (furnace linings, glass, etc.) which are insulators when cold.

It is characteristic of electrolytes that their specific resistance decreases rapidly as the temperature rises, the temperature coefficient for aqueous solutions of metallic salts and of acids being usually between $-1{\cdot}5\ \%$ and $-4\ \%$ per 1° C.

Liquid resistances, as used for motor control (Chapter 29), as a load for generators on test (Chapter 40), or for 'dimming' lights in theatres, consist of electrolytes into which dip metal electrodes; by varying the submerged area of electrodes or the distance between them, the resistance in circuit may be altered within wide limits. The electrolytes most used for such purposes

* *El. Ind. and Invest.*, March 30, 1921, p. 395.

† Some electrolytes are decomposed appreciably by alternating current, but, in general, the chemical effect of one half-cycle is undone by the next half-cycle of current at all commercial supply frequencies, and provided that there is no rectifying action (Chapter 17).

are solutions of common salt, sodium carbonate, and sulphuric acid.

69. Water.—Pure water is an insulator, but practically all substances are to some extent soluble in water, and ordinary 'tap water' and water present in hygroscopic materials as 'moisture' are relatively good (electrolytic) conductors due to the substances dissolved in them.* Water from town mains is sufficiently conducting to be used as a resistance in water-jet lightning arresters (§ 346), and as an artificial load for high-voltage generators.† Water can also be used for an A.C. high-voltage potentiometer but not for D.C. measurements, because it would then be decomposed by electrolysis.

Many of the most used insulating materials are highly hygroscopic, and moisture is probably the commonest cause of insulation break-downs (§§ 71, 72). It reduces both the specific resistance and the dielectric strength of insulating materials and, in conjunction with dust and dirt, it is responsible for much trouble from surface leakage. Where surface leakage is liable to occur, the form and finish of the surface should be such as to offer minimum lodgment for dust. Moisture increases the power losses in dielectrics, but its influence on the risk of break-down is of primary importance. (*See also* §§ 74, 77.)

Insulating Materials.

70. Characteristic Properties of Dielectrics.—The properties which determine the suitability or otherwise of a material for use as a dielectric (§ 4) are: (i) its specific resistance, § 71; (ii) its dielectric strength or break-down voltage, § 72; (iii) its specific inductive capacity, § 60 (*d*); and (iv) its dielectric hysteresis (§§ 60 (*d*), 311). In addition to these electrical criteria, there must be considered the mechanical properties of the material, and its ability to withstand moisture, chemical attack, heat, or other conditions of the proposed service.

Unfortunately, the electrical properties of insulating materials vary widely with many factors, including: Dimensions of test-piece; R.M.S. value, wave form, and frequency of test voltage;

* For conductivity curves, *see* 'Examination of Water by Electrical Methods,' by Digby, *Jour. I.E.E.*, Vol. 45, p. 541.

† 'Artificial Load for Testing Electrical Generators,' by Morcom and Morris, *Jour. I.E.E.*, Vol. 41, p. 137.

temperature and moisture of test-piece; and mechanical pressure on test-piece. The data given in Table 7 have been compiled from many sources, and may be taken as typical values, but as will appear from §§ 71, 72, the range of values is necessarily wide and a high factor of safety must always be provided in electrical insulation to allow for the effect of moisture, heat, and mechanical stress, and for abnormal electrical stress due to pressure surges (§ 345), or to burrs, sharp edges, etc. (the small radius of curvature of which produces intense local stress (§§ 78, 288).

71. Specific Resistance of Insulating Materials: Leakage Current.—It is one of the requirements of an insulating material that its specific resistance should be high (§ 59) in order that the 'leakage current' flowing through the insulation may be small. The actual value of the specific resistance is reduced greatly by the presence of moisture (§ 69) and decreases rapidly with temperature rise. For these reasons the specific resistance of dried specimens tested under laboratory conditions bears no definite relation to the 'insulation resistance' of complete machines, cables, wiring installations, and the like under service conditions. Apart from variations in the specific resistance, it is rarely possible to calculate the effective cross-section of the leakage path offered by the insulation, hence it is usual to take these factors into account by measuring the resultant insulation resistance under service conditions; thence the leakage current may be calculated by applying Ohm's Law (§ 17, and Chapter 40). Insulation resistance measurements are of little value (except as regards ascertaining that the resistance does not fall below a prescribed limit, Chapter 40), unless all the conditions of test are specified in detail. The quantity of moisture absorbed by such materials as fibre or pressboard varies with the duration of exposure and natural drying (without applied heat) may extend over a period of months, the insulation resistance meanwhile rising to 10 or 100 or more times that of the damp material.

The reduction in specific resistance of an insulating material with rise of temperature is often compensated to some extent by moisture being expelled as the temperature rises. It is therefore difficult to obtain consistent data, and it would be unwise to base any predictions upon calculations unsupported by confirmatory tests made under service conditions. From data published by

various investigators it appears that the decrease in specific resistance between 20° C. and 30° C. is from 15 to 25 % for mica; about 30 % for rubber; about 50 % for guttapercha; and from 60 to 70 % for cellulose, fibre, glass, and porcelain. At a temperature of 70° to 80° C. the specific resistance of cellulose, fibre, porcelain, and moulded compositions may be from $\frac{1}{100}$ to $\frac{1}{300}$ of the value at 20° C. The yet greater decrease in insulation resistance at temperatures in the neighbourhood of 500° to 1 000° C. is of great importance in relation to the insulation of sparking plugs, heating elements, and electric furnaces.

Low insulation resistance permits appreciable leakage current to flow through the insulation; the I^2R watts (§ 49) thus dissipated, together with the heating produced by dielectric hysteresis (§ 60 (*d*)), cause the temperature of the insulation to rise. This results in a decrease of insulation resistance, and an increase of leakage current and heating. In extreme cases the insulation is broken down by the combined effect of heat and electrolytic action and, in any case, the losses in the dielectric are objectionable in that they raise the power factor of the charging current; this is of practical importance where cables are concerned (§ 311).

72. **Dielectric Strength: Break-down Voltage.** — Though break-down of insulation may be caused by leakage current (§ 71), it is generally caused by the dielectric stress exceeding the 'dielectric strength' of the material. Both the dielectric stress or pressure gradient and the dielectric strength are expressed in terms of potential difference per unit thickness. The dielectric strength of thin materials such as paper, mica, insulating tape, and pressboard is expressed in volts per mil or volts per mm., whilst that of porcelain, slate, air, etc., is more conveniently expressed in volts per cm. Unfortunately, the dielectric strength is not directly proportional to the thickness of the dielectric but is relatively greater for thin sheets or plates; thus the break-down voltage of a 1-inch plate is much less than 1 000 times that of a sheet 1-mil thick. This lack of proportionality is due partly to the electrostatic field not being uniform and partly to the inability of heat to escape rapidly from the central portions of thick dielectrics; the outer skin surface is also probably a factor of importance in paper and similar materials.

There are wide variations between the values of dielectric

strength determined by different observers, these being explained by the fact that the dielectric strength varies with the following factors :—

(*a*) The structure, homogeneity and quality of the sample.

(*b*) The uniformity or otherwise of the electrostatic field, as determined by the size and shape of the electrodes, and by the thickness and shape of the sample.

(*c*) The thickness of the sample, as explained above.

(*d*) The wave form of the test voltage, and the rate and duration of application of voltage.

(*e*) The moisture content of the specimen.

(*f*) The heat capacity of the electrodes.

It is the *maximum* voltage which causes break-down to occur and the relation between this and the R.M.S. voltage varies with the crest factor (§ 30) of the voltage wave. In X-ray work it is convenient to measure the very high voltages employed by reference to the length of spark gap (in air) which is broken down, and this demands a knowledge of the dielectric strength of air in terms of peak voltage (§ 78), but for machines, cables, etc., it is more convenient to express the dielectric strength in terms of R.M.S. voltage, a sinusoidal test-wave being assumed. The wave form has also an influence on the manner in which the dielectric is stressed and fatigued, so that, for example, a C.C. pressure is less severe on a dielectric than is an A.C. pressure of the same maximum value; this is important in relation to C.C. pressure tests on cables (Chapter 40), but for ordinary operating voltages it may be assumed that C.C. induces the same dielectric stresses as sinusoidal A.C. of the same maximum value (§ 298).

Rapid increase and *prolonged application* of voltage favour break-down, hence it is usual to specify both of these factors, a reasonable rate of increase being 1 000 V per min. when approaching the test pressure or anticipated break-down voltage, and the standard time of application being 1 min.

Moisture reduces greatly the dielectric strength of all hygroscopic insulating materials, and every precaution must be taken to exclude it by impregnating and sheathing fibrous materials. The effect of moisture on oil is mentioned in § 77.

With *increasing temperature* the dielectric strength of all insulating materials decreases; this effect may be masked by the recovery of dielectric strength due to the drying hygroscopic material, or it may be accentuated by the formation of water and acid products at higher temperatures (as where certain condensation products (§ 74, VIII*a*) are used).

From an extensive series of tests by W. S. Flight * it appears that typical values for the reduction in break-down voltages at 100° C. compared with those at 30° C. are :—

For mica, and mica-papers and -cloths	5 to 15 %
For paper fullerboard, and wood	15 ,, 30 % †
For varnished papers and varnished cloths	40 ,, 50 %
For untreated fibre, micarta, and moulded compositions which liberate moisture when heated	60 ,, 80 %

* *Jour. I.E.E.*, Vol. 60, p. 218.

† Sometimes the dielectric strength is greater at 100° C. due to drying-out.

The factors determining dielectric strength are so numerous, and of such great but variable importance, that the adequacy of particular constructions can be determined only by break-down tests under, as nearly as possible, the actual conditions of service.

At the Annual Convention of the American Institute of Electrical Engineers in 1922 (*see Jour. Amer. I.E.E.*, Vol. 41, p. 973) Steinmetz stated that there appeared to be no such thing as a defintie break-down voltage or break-down gradient in solid insulation. A solid insulator appears to be, at least in many cases, a third-class or pyro-electric conductor. On the application of a gradually increasing voltage, the current increases at first in proportion to the voltage, then more rapidly until a certain maximum voltage is reached; at this point the current 'runs away' and rises to the short circuit current of the voltage supply, which generally means the destruction of the 'insulation' (now a conductor) by heat and the elimination of all that can be seen. If, however, for any reason, the amount of energy which can be concentrated on the conducting portion of the dielectric is limited, the disruptive strength of the latter remains unimpared. This may explain why in some cases (*e.g.* in a cable with high ratio of external to internal diameter) part of the insulation can be stressed above the so-called break-down point without changing the insulation. Peaslee (*ibid.*, p. 975) supported this view and stated that the so-called puncture voltage was really the voltage at which, with given material and spacing, the overall volt-ampere characteristic of the path from the conductor to the sheath became negative. This possibility of over-stressing without break-down may be compared with the formation of corona discharge round a conductor in air. In the zone of the discharge the air has become a conductor and the effective diameter of the conductor, as regards distribution of electrical stress in the dielectric, has been increased; complete break-down does not occur until the potential gradient at the surface of the corona exceeds the dielectric strength of the surrounding layer of air.

73. **Classification of Insulating Materials.**—In practice, the selection of an insulating material for a particular application generally resolves itself into a compromise between the desirable mechanical and electrical characteristics; it is seldom possible to obtain in one material the ideal mechanical and electrical properties, to say nothing of thermal, chemical, and other properties. According to the characteristics which are most important in specific applications, insulating materials may be classified in many different ways. In the following paragraphs they are discussed under the broad headings: Solid Insulators (§ 74); Moulded Insulating Materials (§ 75); Insulating Paints, Varnishes, etc. (§ 76); Liquid Insulators (§ 77); Air as an Insulator (§ 78).

74. **Solid Insulators.**—The term 'solid insulators' includes rigid, natural, and artificial materials, such as slate, glass, and porcelain, which are generally used in more or less massive form; and flexible materials, such as mica, rubber, and manufactured

TABLE 7.—*Approximate Constants of Insulating Materials.*
(*Compiled from Various Sources.*) [SEE NOTE ON OPPOSITE PAGE.]

Material.	Specific Gravity.	Megohms per cm. cube (at about 15°-20° C.	Breakdown Volts per mil (at about 15°-20° C.).	Specific Inductive Capacity ϵ.	Material Uninjured by Temperatures up to (about) °C.	*See also* §
Asbestos	3·0	16×10^4	100-110	—	1 000	74, IX*a*
Bakelite products	1·3-1·9	$(0{\cdot}2\text{-}40)\times10^6$	250-500	2·5-5·0	125 with sawdust 200 ,, asbestos 250 pure	74, VIII*a*
,, special	—	20×10^9	500-800	—		
Bitumen, pure	1·0-1·8	—	30-50	2·7	90	74, V*a*
,, vulcanised	1·2	2×10^9	300-350	4·0	43	74, V*a*
Cambric, cotton or silk, varnished: 50 mils	—	$(300\text{-}500)\times10^6$	400-500	4·0-6·0	95	74, IX*d*
5 mils	—	$(300\text{-}500)\times10^6$	800-1 200	4·0-6·0	95	74, IX*d*
Celluloid	1·4	$(2\text{-}7)\times10^4$	350-500	1·2-2·7	75	—
Ebonite (vulcanite)	1·2	$(2\text{-}1\,000)\times10^9$	750-1 000	2·0-3·5	80	74, IV*d*
Erinoid	1·3	$(2\text{-}100)\times10^3$	150-200	—	75	74, VIII*d*
Fibre, vulcanised	1·4	100-5 000	200-400	4·5	200-300	74, IX*d*
Formite, fibre filled	1·4	—	250-500	—	175	74, VIII*b*
,, heat resisting	2·0	—	100-150	—	260-315	74, VIII*b*
Galalith	1·3	$(10\text{-}20)\times10^3$	150-210	—	75	74, VIII*c*
Glass, crown, plate, window	2·5	$(10\text{-}20)\times10^6$	250-350	5·0-8·0	—	74, II*a*
,, flint, lead	3·2-4·5	—	125-150	5·5-9·0	—	74, II*a*
,, special condenser	—	—	1 250	8·5	—	—
,, special conducting	—	500	—	—	—	—
Guttapercha	0·98	$(1\text{-}400)\times10^6$	200-500	2·5-4·5	—	74, IV*e*
Jute, impregnated	—	—	20-40	3-4	—	74, IX*d*
Leatheroid, plain	—	—	350-420	—	90	74, IX*c*
,, varnished	—	—	400-500	—	95	74, IX*c*
Marble	2·5-2·8	500-5 000	50-150	8·3	—	74, I*b*
Mica	2·8-3·2	$(10\text{-}200)\times10^9$	1 500-5 000	5·0-8·0	115	74, III*a*
Mica-cloth or -paper	1·2-1·9	—	300-600	—	—	74, III*c*
Micanite	—	—	500-1 000	4·5	80-115	74, III*b*
Micarta, Paxolin	1·2-1·4	—	300-500	—	95	74, IX*c*
Paper, plain	0·7-1·0	$(5\text{-}100)\times10^4$	150-300	2·0-2·5	90	74, IX*c*
,, varnished	—	$(300\text{-}500)\times10^6$	400-1 000	2·5-4·0	95	74, IX*c*
Paraffin wax	0·9	$(3\text{-}5)\times10^{12}$	300	2·0-2·3	—	74, VI*a*
Pitch	1·1	—	50	1·8	—	75, I*b*
Porcelain, wet process	2·3-2·4	$(1\text{-}1\,000)\times10^6$	200-300	4·4-6·0	1 300 (special)	74, II*c*
,, dry process	2·0-2·3	—	100	—	—	74, II*c*
Pressboard, plain	—	10 000	200-350	—	90	74, IX*c*
,, varnished	—	—	250-400	—	95	74, IX*c*
,, oiled	—	—	700-900	—	95	74, IX*c*
Quartz, silica	2·2-2·7	$(1\text{-}2)\times10^8$	—	3·5-4·5	1 100-1 200	74, II*b*
Resin	1·1	5×10^{10}	280	2·6	—	74, VII
Rubber, plain	0·9-1·0	$(10\text{-}15)\times10^9$	400-700	2·0-2·5	—	74, IV*a*
,, vulcanised	1·3-1·8	$(1\text{-}10)\times10^9$	300-600	3·0-5·0	—	74, IV*a*
Shellac	—	$(2\text{-}10)\times10^9$	40	2·75-3·0	—	75, II*b*
Siluminite	2·0	2×10^6	250-330	—	315	—
Slate	2·5-3·0	100-50 000	20-40	6·5-7·4	—	74, I*a*
Sulphur	1·9	$(4\text{-}100)\times10^9$	—	3·0-4·0	—	—
Varnish, oil	—	—	800-1 000	—	—	76
Wood, plain, dry	0·4-1·3	$(1\text{-}50)\times10^6$	10-15	2·5-7·0	90	74, IX*b*
,, impregnated	—	—	50-150	—	95	74, IX*b*
Benzine	0·88	1400	—	2·4	—	—
Castor oil	0·97	—	—	4·8	—	—
Petroleum	0·85-0·9	—	160-170	2·0	—	77 (1)
Turpentine	0·87	—	240	2·2	—	—
Air, atmospheric pressure	—	Infinite	95-100	1·0	—	78
,, at 10 atmos.	—	,,	600	—	—	78

fibrous product (papers and textiles), which are used for wrappings or coverings and for other applications where flexibility is required. Waxes, compounds, gums, and resins may fairly be considered as solid insulators, though they are liquid under some conditions of temperature and in some methods or stages of application. Moulded insulating materials are solid in their service condition but an essential feature of these materials (§ 75) is their initial plasticity or 'mouldability.'

I. Stones.—(*a*) *Slate* is used extensively for the panels of low-voltage switchgear, etc. There are frequently metallic veins in the material, hence all live parts should be insulated by micanite washers and bushes or equivalent means. The front and edges are generally enamelled. Treatment with oil counteracts the hygroscopic nature of the material. Inferior slate contains hard spots and is liable to flaking.

(*b*) *Marble*, when polished, provides a handsome mounting for switchgear and instruments but is liable to contain conducting veins, hence live parts should be insulated (*see* (*a*)).

(*c*) *Steatite* (*Soapstone*) is the massive form of talc, a silicate of magnesia. Pieces to be used as insulators in heating and cooking apparatus, arc lamps, sparking plugs, etc., may be machined from the natural mineral, or the latter may be pulverised, mixed with a cement, and moulded to form. After kilning the steatite is extremely hard, less brittle than porcelain, but porous. A glaze may be applied to exclude moisture. The specific resistance falls rapidly above 300° C.

(*d*) *Concrete* cannot be relied upon for insulation except where low voltages are concerned. It is, however, useful in cellular switchboards (§ 378) as a 'non-conducting' structural material for partitions, etc., the actual insulation being provided by porcelain. Protective reactance coils (§ 340) are sometimes encased in concrete.

II. Vitreous Materials.—(*a*) *Glass* varies widely in electrical properties according to its chemical composition. It is impervious to moisture and the transparency of the material facilitates inspection. The principal disadvantages are its brittleness and its high temperature coefficient of expansion. Where used, glass should be annealed. The specific resistance decreases rapidly above about 200° C. Glass is an electrolytic conductor (§ 68), and there is considerable surface leakage over those glasses which are attacked by moisture.

(*b*) *Quartz* (*Silica*) has practically zero temperature coefficient of expansion and is, therefore, not cracked by wide and sudden variations of temperature.

Note to Table 7.

The data in this table must be regarded as only approximate; where exact values are of importance, special tests must be made because the electrical properties of all materials vary widely with the sample and with the conditions of testing. To facilitate comparison, the break-down voltage of specimens of the thicknesses commonly used in practice have been reduced to V/mil by simple proportion. Actually, the break-down voltage does not vary directly with thickness (§ 72) but the values per mil when multiplied by the thickness actually employed will give approximately the break-down voltage of the latter; a large factor of safety must be allowed (§ 72). Arithmetically (but *not* electrically, § 72): 1 V/mil = 39·4 V/mm.; 1 V/mm. = 0·0254 V/mil.

This property makes it useful for pyrometer-sheaths, supports for heating elements, special lamp bulbs (Chapter 25), sparking plugs, etc. Due to its refractory nature quartz is difficult to work, and this is the chief hindrance to its more general utilisation. The specific resistance decreases rapidly above 400° C. Quartz is less brittle than porcelain and is sometimes used on the moving parts of oil switches.

(c) *Porcelain* for electrical purposes should be vitreous throughout and a 0·5 °/$_{o}$ alcoholic solution of fuchsin dye should not penetrate into broken test-pieces, even when the latter are immersed for 24 hrs. under a pressure of 2 000 lbs. per sq. in.* Porcelain is not so brittle as glass, and the special qualities now used for transmission line insulators have a low temperature coefficient of expansion and are able to withstand indefinitely alternate immersion in boiling and freezing water. Other applications include the support and insulation of conductors, contact-pieces, terminals, etc., on switchboards and in all kinds of apparatus and accessories. The compression strength of porcelain is high, but the material should not be subjected to tension. Pieces of relatively complex form can be moulded, but the material cannot be worked after firing. Porcelain resists chemical attack and may be exposed to high temperatures, but the specific resistance decreases rapidly above 200° C.

Porcelain is made from kaolin (china clay) and felspar as main ingredients. The details of composition and manufacture of special qualities are carefully-guarded secrets. Simple pieces of small dimensions may be made by moulding a damp mixture of the ingredients under high pressure, but it is generally admitted that a better product is obtained by mixing the ingredients with sufficient water to form a plastic mass (*wet process*), which is formed into the desired shapes by hand or by simple tools (as distinct from presses). Dry-moulded porcelain is apt to be porous.

After a preliminary drying the pieces are fired at 1 200°-1 300° C. The glaze is of the same general composition as the porcelain, but is a more fusible mixture and therefore melts to form a glass-like film on the surface. Though the glaze has considerable dielectric strength and does 'seal' pores it should not be taken as reducing in the slightest degree the necessity for a vitreous structure throughout the porcelain. The glaze should be regarded simply as a self-cleaning, dirt- and weather-resisting 'finish.'

III. Mica and Mica Products.—(*a*) *Mica* is a mineral consisting of silicates of aluminium, potassium, and magnesium, with certain impurities, of which iron oxide is electrically the most objectionable. Amber (Canadian) mica is soft and is recommended for use between commutator bars. White and ruby micas (Indian) are harder and of higher dielectric strength; they are recommended for sparking plugs and condensers. Spotted mica is suitable for use in electric heaters. All varieties of mica are characterised by their laminated structure; the plates can be split and resplit almost indefinitely. Sheets 1 mil thick should not crack when wrapped round a lead pencil. In use, the sheets should be clamped, or otherwise subjected to mechanical pressure, in a direction perpendicular to the plane of cleavage. Mica is disintegrated by oil; it is also disintegrated at temperatures above 500° C. (as reached in heating elements, etc.) unless it is subject to compression. Of all flexible insulating materials mica is the most resistant to high temperatures; mica insulated windings have operated

* Standard porosity test for porcelain insulators for high-tension lines (B.E.S.A. Report 137).

without deterioration at 200° C., but a lower working temperature is desirable (§ 80).

Mica sheets 12 ins. square are now rarely found. Sheets 2 ins. × $1\frac{1}{2}$ ins. are about the smallest size of any commercial value; these cost a few pence per lb., whereas the largest selected sheets may cost more than £1 per lb. In such applications as sparking plugs it is possible to build up pure mica insulation by superimposition of small sheets, and in other applications it is sometimes possible to use larger sheets with the joints staggered in consecutive layers. Generally, however, it is more satisfactory to use one or other of the mica products mentioned below.

(*b*) *Micanite.*—The best micanite sheets are built up from mica splittings, about 1 mil thick and 2 or 3 sq. ins. in area, cemented together with shellac or similar binder and consolidated by heat and mechanical pressure Though the maximum dielectric strength of micanite is lower than that of mica, there is less variation in the dielectric strength of the manufactured product, due to metallic inclusions in the mica being distributed throughout the micanite. *Moulding micanite* softens at about 95° C. and can then be pressed into shape for commutator end rings, slot linings, etc. A harder *commutator micanite* with less than 5 °/o of a binder which does not soften at 95° C. is made for use between commutator bars and in other places where flat sheets are required. *Flexible micanite* is made with a flexible binder (generally containing some oil) and is flexible at all temperatures; it is used to insulate windings. *Heat-resisting micanite*, made with water-glass (sodium silicate) as binder can be used at temperatures up to 500° C. without injury; it is suitable only for low voltages (say, 250 V) and must be kept dry.

According to requirements, various grades of micanite are obtainable in sheets up to 3 ft. square and in thicknesses from 5 mils to $\frac{1}{8}$ in. or more.

(*c*) *Mica Papers, -Cloths, etc.*, consist of one or more layers of mica splittings supported on one or both sides by Japanese or other special paper, silk, or cloth, to which it is attached by a quick-drying copal or shellac varnish. Micanite-cloth is stronger than micanite-paper; so also is micanite silk, with the further advantage that it is thinner and more flexible than cloth. In all three cases the dielectric strength is practically that of the mica alone. *Micafolium* (micarta folium or mica-paper) can be built up into tubes, etc., and is used extensively to insulate high-voltage windings. Thick tubes and shields are sometimes built up from micanite and impregnated paper. *Micarta* is *not* a mica product, *see* section 9 (*c*).

IV. Rubber and Rubber Products.—(*a*) *Rubber*, a complex compound of carbon and hydrogen, is the coagulated latex of certain trees and vines. Synthetic rubber can be made, but is, at present, more costly and less satisfactory than the natural product. Para rubber is generally considered to be the best for electrical work. Pure rubber strip is used to protect copper from the sulphur in vulcanised rubber (§§ 283, 285) but, as pure rubber is hygroscopic and oxidises rapidly, it may not be exposed to air.

(*b*) *Vulcanised Rubber* (V.I.R.).—When mixed with 5 °/o or less of sulphur and heated to 150°-160° C., rubber is *vulcanised* and in this form it is tough, elastic, non-hygroscopic, and less affected than pure rubber by heat. Vulcanised rubber is the standard insulating material for low voltage cables (§ 283). Even the vulcanised product is deteriorated by light, air, ozone (§ 287), oil, and grease; and it deteriorates in service if heated above 50° C.

As used to insulate conductors, V.I.R. contains from 30-60 °/o of pure rubber, according to the requirements to be met,

together with litharge (up to 10 °/ₒ or so), whiting (up to 25 or 30 °/ₒ), zinc oxide (from 20-50 °/ₒ), and colouring materials as required. The relative proportions of the inorganic ingredients vary widely according to the practice of individual makers or the specifications of purchasers. The general effect of these ingredients is to toughen the product and facilitate vulcanisation. It is remarkable that rubber can carry 50 °/ₒ or more of mineral matter without losing its characteristic elasticity.

(c) *Tough Rubber Compound* (C.T.S.) is a 'mechanical' rubber and should be regarded primarily as protection against rough-usage, corrosion, etc., though it has, of course, some insulating value as well (§ 283).

(d) *Ebonite, Vulcanite or Hard Rubber* is vulcanised rubber containing from 30-50 °/ₒ of sulphur and subjected to prolonged curing at 150° C. The material is hard and brittle; can be machined and polished; softens between 60° and 100° C. and can then be moulded into simple shapes. It is much used in instruments, telephone parts, etc. Sheets are made in moulds faced with metal foil to obtain a planished surface; sufficient of the metal enters the ebonite to reduce the surface insulation of the latter. The original surface should therefore be removed where surface leakage is to be avoided. When exposed to sunlight or ultra-violet rays the surface of ebonite undergoes decomposition and surface leakage ensues. Ebonite-mounted resistance boxes, etc., should be kept away from sunlight, and the surface should be washed occasionally with distilled water. Ebonite is not suitable for immersion in oil.

The mechanical and heat-resisting properties of ebonite can be improved by the addition of certain mineral ingredients to the mixture before curing; the dielectric strength is lowered however. *Stabilit* is a proprietary composition of this type.

(e) *Guttapercha* is similar to, but chemically distinct from, rubber. It is inferior to rubber as an insulator and oxidises in air; it softens about 65° C. It is unaffected by water and its main use is in the insulation of submarine cables.

V. Bitumen.—(a) *Bitumen or Asphalt* is a natural product (mineral pitch) consisting of a complex mixture of hydrocarbons with more or less inorganic matter. The best crude material is in the Trinidad Lake deposit, and is a semi-fluid material which softens and melts between 80° and 100° C. Refined bitumen is used in the manufacture of certain insulating varnishes, impregnating compounds, and joint box compounds. It is also used round cables which are laid solid (§ 290). No form of bitumen should be exposed to oil.

(b) *Vulcanised Bitumen* is made by a process similar to the vulcanising of rubber (IV (b)) and is used to insulate cables. It is brittle at low atmospheric temperatures and softens at about 38° C.; for other properties *see* § 287.

(c) *Elaterite* (*Elastic Bitumen or Mineral Caoutchouc*) is a soft grade of asphalt.

(d) *Gilsonite* is a hard grade of asphalt which melts at about 135° C.

VI. Waxes and Compounds.—These are used to fill joint boxes, instrument transformer cases, terminal boxes, etc., and to impregnate absorbent coverings of wires and windings to exclude air and moisture, and contribute to the insulation strength. The waxes used include beeswax, ceresine, montan, and paraffin wax;

and the composition of compounds varies widely with the needs of individual cases. Soft wax (ozokerite, etc., § 283), melting at 50°-70° C., is used to finish cotton-braided wires. Mixtures of bitumen and pitch with various waxes yield hard, tough compounds for joint boxes, etc., and can be obtained with melting-points from 65°-150° C. as required. *Chatterton compound* consists of guttapercha, tar, and resin, and is very elastic.

Paraffin Wax is often used to render wood acid-proof, and to render wood and paper non-hygroscopic; applied to the edges of rolled oiled tape, it excludes moisture. As a filling for instrument transformers, etc., this wax has the advantage of being a good insulator which fills all crevices and is normally solid; in the event of undue heating in service, the wax melts and then circulates (like oil) thus improving the cooling facilities.

VII. Resins. Natural resins (new or fossilised) are oxidised exudations from certain trees or insects thereon. *Shellac* is refined lac in flake form, and is used in the preparation of various varnishes and in making micanite and similar products. *Copal* is another natural resin; its applications are similar to those of shellac. (*See also* §§ 74 (viii), 76.)

VIII. Synthetic Products.—(*a*) *Bakelite* is the trade name of a series of 'condensation products' or 'synthetic resins' developed by the researches of Dr. Baekeland, from whom they take their name. 'Bakelite-A' is formed by the action of phenol (carbolic acid) on formaldehyde at a temperature below 100° C. This product is used as a varnish or to impregnate paper, etc., or it is mixed with porous 'fillers' to form moulding compounds (§ 75). After application for one or other of these purposes, the resin is converted to 'Bakelite-C' by heating under a pressure of 100-150 lbs. per sq. in. at a temperature between 150° and 200° C. according to the makers' instructions for the particular application concerned. 'Bakelite-C' is an amber-coloured solid with good mechanical and electrical properties; it is unaffected by water, oils, and all but strong acids and strong alkalis; it is not softened by heat but chars at from 250°-300° C. 'Bakelite-B' is an intermediate product which is sometimes preferable to the A-product for use in moulding compositions.

Bakelite, converted to the C-form after application or moulding, is suitable for use where a solid, inflexible (but relatively tough) sheath or filling is to be produced by surface treatment or impregnation respectively. Small parts can be made of bakelite alone, but for most purposes it is sufficient and cheaper to use a composition (§ 75). The final 'condensation' (to form C) liberates water which should be removed by vacuum-drying in the case of coils.

(*b*) *Formite* is a British-made phenol-formaldehyde product used in the preparation of moulding powders (§ 75).

(*c*) *Galalith* is a dried-milk product which can be moulded or bent but is hygroscopic. Insoluble casein is treated with formaldehyde and subjected to mechanical pressure.

Erinoid is also made by the action of formaldehyde on milk proteins. It can be machined and softens in boiling water. Its electrical properties are similar to those of red fibre, but it is less hygroscopic than the latter.

IX.—Fibrous Materials and Products.—(*a*) *Asbestos* is used in insulating tapes, sheets, and varnishes where resistance to heat is required. It is highly absorbent and can be impregnated satisfactorily with materials of higher dielectric strength than itself. Mechanically, it is weak. Resistance nets are woven with warps of spun asbestos and wefts of suitable resistance wire. Where used as a fireproof braiding asbestos should be varnished to prevent it acting as a " wick

for oil, if there is any risk of the latter being present. Asbestos is used in heat-resisting moulding compositions (§ 75). A wet paste of asbestos protects the insulation of conductors when welding joints in the latter. Lagging for thermal storages, etc., may contain asbestos as an ingredient. Asbestos is attacked by acids and alkalis.

(*b*) *Wood*, when dried and impregnated with oil, is used as a tank lining in oil-immersed switchgear to prevent arcs from coming into contact with the metal. Maple is useful for such work. Wood impregnated with paraffin wax is acid-resisting and moisture-proof. Hard-wood rods are used as handles for operating arrester charging and opening isolating links.

(*c*) *Paper*, though highly hygroscopic, is used in many applications on account of its flexibility and good dielectric properties. Dry paper, wrapped loosely, is used to insulate the conductors of dry-core (air-space) telephone cables; a lead sheath is used to exclude moisture, and the advantage of the dry paper insulation is that the inductive capacity of the cable is kept low and attenuation and distortion of speech currents are reduced. In cables for lighting and power service substantial thicknesses of paper are required (§ 280), and the paper is impregnated to increase its dielectric strength and to exclude air films (§ 79). Rosin oil is the principal ingredient of the impregnating compound used where the paper is to remain flexible; the compound must not be so fluid as to drain out of the paper. Non-drying impregnating materials are displaced by moisture, hence a sheathing of lead or vulcanised bitumen is necessary (§ 287). Paper which is to be used as insulation exposed to air may be impregnated with a drying varnish or bakelite.

Manilla paper is generally considered to be the best for electrical purposes, but there are many papers now available for the special requirements of various applications. Japanese papers are used in mica-paper tapes. Papers made from cotton and linen rags are used in condensers. Wood-pulp papers are highly absorbent but mechanically weak.

Paper may be impregnated with oils before or after its application to conductors. Thin strong paper coated with successive layers of flexible-drying varnish is used in instrument and machine windings and in condensers; this material is often called oiled paper. Paper soaked in paraffin wax is used in condensers; the wax cracks if bent.

Micarta consists of paper which is dried, covered with insulating varnish, and built into sheets, tubes or rods; heat and mechanical tension or pressure are applied to consolidate the successive layers and, when cold, the product can be machined. *Bakelised micarta or paxolin* is made by using liquid bakelite (instead of shellac, copal, etc.), which is subsequently converted to the C-form (see VIII *a*). Micarta with shellac as binder softens at about 80° C.; bakelised micarta can be used at 100°-110° C. or, if asbestos paper be employed, up to 180° or 200° C. Paxolin can be used in oil; its toughness is a valuable property; this material is often used in preference to wood or vulcanised fibre.

Paper Boards, Fibre, etc. Some of the materials coming under this heading are produced by paper-making processes, whilst others (using similar raw materials) are subjected to chemical, mechanical, and thermal treatment which first reduces the cellulose to a more or less gelatinous condition and then consolidates the whole to a horn-like material showing little or no trace of fibrous structure.

Presspahn, Pressboard, or Fullerboard is a paper made, in thickness up to ½ in., from hemp, rags, wood-pulp or mixtures of these. It is highly absorbent and is oil-impregnated for use in transformers, oiled or varnished for use in air, or impregnated in the same way as coils. *Leatheroid, fibroid, fish paper or tarpon*

paper is made in thickness up to ⅛ in., from cotton rags subjected to chemical treatment. It is a tough, horny material of higher dielectric strength than pressboard. It is unaffected by grease or oil and is much used between windings, for slot and core insulation, etc. If required, it may be impregnated, varnished, or waxed. *Whalebone paper, horn fibre, and red rope paper* are practically identical materials; they are made like leatheroid, but from a hemp base, and are used for similar purposes. Their dielectric strength is lower than that of leatheroid. *Vulcanised fibre* is made in many varieties, most of which bear trade names and are made by secret processes. In all cases the basic ingredient is some form of cellulose which is treated chemically to obtain a horn-like structure. Mineral ingredients are added for colouring or other desired physical properties. Vulcanised fibre is highly hygroscopic and swells when moistened without, however, such disintegration as is liable to occur in boards which are built up layer by layer. Vulcanised fibre is sold in sheets, rods and tubes, and can be machined; it may be waxed or varnished to exclude moisture. It is insoluble in water or oil, and is charred by strong acids or high heat. Fibre containing asbestos is disintegrated very slowly by fire.

(*d*) *Textile Materials* used for insulating purposes include cotton, linen, jute, and silk. The uses of woven asbestos have already been mentioned (Section IX (*a*)). *Cotton and silk* are used in one or two layers for the covering of bell wire and flexibles (§ 285), the actual insulation being provided by one or two layers of rubber next to the conductor. Cotton-covered bell wire is waxed to exclude moisture and to provide a good finish. Cotton or silk is used as the sole insulation on small wires for instruments, small motors, etc.; generally, it is advisable to dry and varnish or impregnate the winding to exclude moisture and to reinforce the insulation provided by the fibrous material. *Artificial cellulose silk* is an efficient and economical substitute for real silk in the insulation of small wires for fan armatures, instruments, etc.; when dissolved it forms a highly insulating varnish. Cellulose acetate from which artificial silk is made is non-inflammable. The spun thread is thicker than real silk, but its insulating properties under varying conditions of temperature and humidity are more than proportionately higher. This material and tests upon it are described by W. R. Kennedy, *El. Rev.*, Vol. 87, p. 836.

Jute is used as insulation on cables, being then impregnated like paper and for the same reasons. It is also used as a filler between the cores of multi-core cables, and as a bedding and covering for armouring. *Hemp* is used as a core for stranded cables and as a packing for insulator pins.

Oiled (*or varnished*) *Tape or Cloth* consists of cotton, silk, duck, canvas, etc., prepared by repeated dipping in oxidised linseed oil or a special varnish, each coat being baked before the next is applied. Such materials owe their dielectric strength mainly to the oil or varnish. They are non-hygroscopic, strong, and flexible and are used extensively as wrappings for individual conductors, for coils, and between windings. "Empire" cloths and paper belong to this class. Untreated tapes may be dried and impregnated, after application, with varnish, compound, or bakelite. Yellow oiled cloth is treated with oil alone; black oiled cloth is treated with a mixture of oil and asphaltic matter and has slightly higher dielectric strength. These materials are more flexible than paper and much less hygroscopic. Varnished (or oiled) cambric forms an excellent dielectric for high voltage cables particularly where great flexibility is required; the cambric should be served, as wound, with a non-drying compound to exclude moisture and air (§ 79). The oiled fabric is unaffected by oil.

Rubbered Linen Tape (coated on one side with rubber) is useful in insulating machine windings.

Adhesive or Friction Tape is coated with a tacky compound which gradually 'sets' when exposed to air. Though it has considerable insulation value, this material should *not* be counted as part of the insulation, but should be regarded merely as holding in place the rubber tape, etc., which forms the true insulation.

75. Moulded Insulation Materials.—This heading includes a great variety of materials (mostly mixtures) which can be moulded in a die to produce pieces accurate in dimensions and requiring little or no machining. Heat and mechanical pressure have usually to be applied during the moulding process, and these convert the raw materials (by physical or chemical changes or both) into a homogeneous mass. There are also cold-moulding preparations which set like cement. The electrical properties of moulded insulators vary widely with the composition. The principal applications of these materials are where identically similar parts are required in sufficient numbers to justify the cost of the dies. The more intricate the pieces, the greater the saving by moulding, once the cost of the dies is covered. The exact compositions of preparations for moulding are trade secrets, but the ordinary engineer is concerned only with the general nature and applications of the materials. The design of dies and the manipulation of mixtures to meet specified requirements are matters for specialists. The important point to be remembered is that one-piece moulded insulators frequently replace many loose components and reduce assembly work to a minimum; metal inserts can be placed in the die and thus become mechanically one with the insulation.

All moulding compositions consist essentially of a 'filler' and a 'binder,' together with such special additions as colouring ingredients. According to the type of binder employed, the compositions may conveniently be classified as: (I) Cold-moulding compositions, using an asphaltic solution or a water cement as binder. It may be necessary to heat the moulded pieces to dry them or to set the binder. (II) Hot-moulding compositions, using (*a*) shellac, rubber, or other bond which melts or softens when heated and sets on cooling; or (*b*) synthetic resins which are mouldable whilst in their primary or secondary form but are converted by heat to a rigid solid.

I. Cold-moulding Compositions.—(*a*) *Portland Cement* may be used as binder with asbestos as filler for simple pieces which are required to stand high tempera-

tures (400° C.). The material is naturally hygroscopic but may be waterproofed. *Lime-silica cement* and asbestos is claimed to withstand temperatures up to 650° C. without serious deterioration. *Sodium silicate* (*water glass*) gives a hygroscopic product of low mechanical and electrical strength, but one which resists heat well.

(*b*) *Pitch or Asphalt* is dissolved in an appropriate solvent, mixed with wood, fibre, asbestos, sand, etc., and heated (after moulding) to expel the solvent. Intricate shapes can be made with a good finish, but the product is not suitable for machinery; it will stand about 300° C., and is non-absorbent.

Compositions of type (*a*) are of low dielectric strength (20-50 V per mil) and are useful for shields and mountings to withstand heat rather than electrical stress. Compositions of type (*b*) are of higher dielectric strength (75-150 V per mil), and are suitable for actual insulation up to 500 or 600 V. Hot-moulded compositions are better electrically and mechanically, but the most refractory of them cannot be used above about 300° C.

II. Hot-moulding Compositions.—(*a*) *Rubber*, mixed with sulphur and various fillers, can be moulded under heat and pressure, and then converted to ebonite (§ 74, IV (*d*)) but the applicability of the latter in this connection is limited, because it begins to soften about 60° C. The dielectric strength is high, say 400 V per mil.

(*b*) *Shellac* as binder for mica produces the valuable material micanite (§ 74, III (*b*)) which can be moulded into simple shapes. Shellac can be used as binder for many other fillers, but its utility is limited by its softening between 65° and 90° C. Shellac and cotton fibre or similar material gives a good finish and high dielectric strength (say 200-300 V per mil.) and is suitable for use in sheltered situations.

(*c*) *Synthetic Resins* (Bakelite, Formite, § 74, VIII (*a*, *b*)) find one of their most important applications in the preparation of moulding compounds. Sawdust, fibre, asbestos, mica, slate, etc., are used as fillers according to the properties desired. The makers of the primary condensation product frequently mix this with appropriate fillers, convert the resin to the B-form (§ 74, VIII (*a*)), and grind the product to form a moulding powder which is supplied to licensed moulders. The powder is reduced to about one-fourth of its 'loose' volume when compressed in the hot moulds at from 500-2 000 lbs. per sq. in., and 150°-200° C., according to the makers' instructions. The final product (with the resin in the C-form) is accurate within good machine-shop limits, say ± 2 mils, and has a valuable combination of properties. With cotton, hemp, sawdust, or similar filling, a machinable product is obtained which will withstand temperatures up to 150° C. and has a dielectric strength between 250 and 500 V per mil, according to its composition. Heat-resisting fillers, such as asbestos, sand, etc., yield non-absorbent products, which are almost or quite unaffected by acids, alkalis, and hot oil; these products are unsuitable for machining, withstand temperatures up to 250° or 300° C., and have dielectric strengths from 100 to 150 V per mil.

76. Insulating Paints, Varnishes, etc.—Though paints, enamels, and varnishes are liquid when applied to the parts or material to be insulated, it is the dry material left by evaporation of the solvent, or the solid matter formed by combined oxidation and drying, which constitutes the actual insulation. Liquid compounds which set by evaporation of solvent or by chemical changes caused by heat (§ 74, VIII (*a*)) can be used for deep penetration or

complete impregnation, but materials which depend upon oxidation for their solidification can only be used on surfaces or for tapes, etc. (§ 74, IX (*d*)). At one end of the scale there are non-drying compounds (resin oil, etc.) used to impregnate paper cables, and at the other end there are the enamels which dry as a tough, flexible coat which is sufficient insulation for wires to be used in low-voltage instrument coils, bells, etc. Vacuum impregnation is essential for most windings for use in the tropics or monsoon countries, especially for fan motor windings. Asphaltic material may be used to produce a black varnish, or the varnish may contain no colouring matter, in which case it produces a colourless, yellow or brown coat according to the gum or oil which forms the residual constituent.

Air-drying Spirit Varnishes, used for finishing or for quick repair work, consist of a gum or resin in a solvent which evaporates quickly when exposed to air. The coating dries in 1 hr. or less, but is relatively brittle and not able to stand heat and vibration without cracking. *Air-drying oil varnishes* take longer to dry (12-24 hrs.) but produce a much tougher and more flexible coat. *Baking oil varnishes* need stoving for from 3-9 hrs. at a temperature of 80°-100° C. and yield a hard, tough coat of maximum mechanical and electrical strength. *Synthetic resin varnishes* are converted to the C-form (§ 74, VIII (*a*)) by stoving for several hours at about 150° C., the coils treated being then set solid in a mass of rigid insulation. A final drying *in vacuo* is needed to remove water liberated by the condensation process. *Acid-proof paints* should be regarded as finishing materials, affording protection against acid fumes but of no electrical insulating value.

The general precautions to be observed when using insulating varnishes are: (i) To dry thoroughly the material to be varnished. This is done by stoving; the dried coil, etc., may then be coated by brushing or dipping, but vacuum impregnation is preferable where applicable. (ii) The varnish itself must be dry, clean, and of the right consistency; the viscosity affects the penetration and adherence obtained. Evaporation of solvent must be made good at frequent intervals, a hygrometer and thermometer being used to check the consistency. The density of an average insulating varnish decreases or increases about 0·3 to 0·35 % per 5° C. rise or fall from 15° C.

A good oil varnish is practically proof against acid, oil, and moisture. A valuable effect of impregnating windings is to increase the heat conductivity of the insulation as a whole.

77. Liquid Insulators.—The only insulators which are liquid during normal service are oil and carbon tetrachloride. As

generally employed the purpose of such insulators is to assist in removing heat (as in transformers) or to quench arcs (as in switches and fuses). The dielectric strength of oil is higher than that of air (§ 78), but the main reasons for its use are as stated. Due to its convection currents, oil is more effective than a solid filling in removing heat, within the range of thermal conductivities of the insulating materials available.

(1) *Transformer and Switch Oil.*—Mineral, animal, and vegetable oils are all good insulators, of practically equal value when pure and dry, but mineral oils have the advantage of being practically immune from oxidation and the development of acidity in service; also, they are less subject to sludging and carbonisation by heat. Resin oil has been mentioned favourably in Germany for use in transformers because it forms no tar deposits; it is, however, quickly carbonised by arcs if used in switchgear. The oils employed almost universally for transformers and switchgear are petroleum distillates. The particular grade employed is called *transil oil.* Specifications vary somewhat, but the properties generally demanded *in the oil as delivered* * are: An unmixed, clear, refined product of sp. gr. between 0·85 and 0·90 at 20° C. Viscosity (Redwood), say, between 100 and 200 secs. at 20° C., and between 60 and 75 secs. at 50° C. Practically free from moisture, sand, fibres, etc.* Free from alkali and sulphur. Acid content not more than 0·02 % expressed as H_2SO_4 (often 'no trace of acid' is specified). Setting-point (cold test) not above − 15° C. for switch oils, and not above − 4° C. for transformer oils. Flash-point not below 145° C. for transformer oil, and 160° C. for switch oil. The loss by evaporation when heated for 6 hrs. at 100° C. should not exceed 0·5 %; no deposit should form, and no acidity should be developed during this heating. Tests for sludging (which should not occur) involve bubbling air through oil at, say, 110° C. for two or three days.

Though a specification of this nature ensures that a suitable oil is obtained, the influence of the various clauses is not so definite as might be expected. The viscosity of the oil affects the rate of cooling of transformers and, naturally, the viscosity at the normal working temperature should be considered; the viscosity at atmospheric temperature is of little practical importance. It is doubtful whether viscosity, within the range of practical values, has appreciable influence on the speed of quenching arcs at switch contacts. There must be no risk of a switch oil congealing at low atmospheric temperatures, but stiff oil in a cold transformer is of little importance provided that the viscosity becomes correct as the transformer heats up. The flash-point test is useful only as excluding oils with highly volatile constituents. The maximum temperature in service is always far below the flash-point (§ 80) except at submerged arcs, where burning cannot occur; if arcing occurs in contact with air the oil will ignite whatever its flash-point. A small loss by evaporation, on heating, is desirable, but the rate of loss naturally becomes much smaller as evaporation proceeds. In modern transformers volatile matter can escape only slowly, if at all, from the tank; oil-switch tanks are provided with pipe-vents to free air.

Sludging in transformer oil forms deposits which clog the circulating passages, and reduce the rate of heat-transmission from transformer to oil and from oil to tank. The deposits are oxidation products and have an acid reaction; their

* The oil must be filtered and dried before use as explained below.

formation appears to be hastened by a catalytic action on the part of copper. Forced circulation of oil prevents the sludge from settling; periodic filtration is desirable. Russian oils contain less tar and give less trouble from sludge than do American oils.

It is useless to specify voltage break-down tests for oil as delivered, because oil delivered in bulk inevitably contains fibrous and other foreign matter and some moisture (up to, say, 0·1 %). Recent research * indicates that break-down tests on oils with needle points or point and plate electrodes do not indicate the quality of oil as regards wetness or dirt, and therefore give a fictitious consistency of results. After filtration and drying, a good transformer or switch oil should not break-down below 20 000 V when tested on a 0·15 in. gap between spheres of ½ in. diameter submerged at least 2 ins. Filtration and drying may be effected by forcing the oil through a filter-press containing sheets of absorbent paper.

The break-down of oils appears to be due generally to fibrous particles forming chains between the electrodes under the influence of the intense electrostatic field. The remarkable effect of a trace of moisture in reducing the dielectric strength of oil (1 part of water in 10 000 of oil may halve the break-down voltage) is explained by the moisture being absorbed by the fibrous particles. If oil be cleansed by a colloid or membrane filter its break-down voltage, on a 0·15 in. gap between ½ in. spheres, may be 65 000-90 000 V or higher.

(2) *Carbon Tetrachloride* is incombustible and comparable with mineral oil as an insulator. It has been tried as a substitute for mineral oil in oil switches but is subject to serious disadvantages, *viz.*: (1) It evaporates at atmospheric temperatures. This may be prevented by a layer of glycerine, but the latter is a conductor and is liable to get on the insulators; also, glycerine corrodes copper. (2) It corrodes copper, but protection can be obtained (except at the contact faces) by tinning. (3) It has no lubricating value. (4) It is about twice as heavy as mineral oil (sp. gr. 1·6 compared with 0·87). (5) It has anæsthetic effects, is detrimental to health, and dissolves rubber.

Carbon tetrachloride boils at 76° C. and freezes at − 27° C. Its only advantage for switchgear appears to be its incombustibility, and this is outweighed by its many disadvantages. It is, however, used as a filling for certain high tension fuses.

78. Air as an Insulator.—Wherever it is applicable as insulation, air has the advantage that it needs no preparation or maintenance. Should a voltage break-down occur the full insulation is restored by fresh air directly the discharge ceases, unless the ionised air cannot escape—in which case the insulation may be low for some time. Though air itself costs nothing, a structural support has to be provided to hold conductors apart in air, and porcelain or equivalent insulators have to be provided between the conductors and their supports; these insulators are electrically in parallel with the air between the conductors. Again, though air is a 'self-mending' insulator, a break-down may result in

* See communication from B.E.R.A., 'Research on Insulating Oils,' *El. Rev.*, Vol. 89, p. 687.

injury to the conductors by arcing, or in the establishment of pressure surges (§ 349) which damage the insulation of machine windings, etc., at other points, in the system.

The dielectric strength of compressed air is considerably higher than that of air at atmospheric pressure, and compressed air has therefore been used in E.H.T. condensers and instruments, mainly for experimental purposes.

There is a fairly definite relation between the maximum value of an alternating voltage and the length of air-gap across which sparking occurs between stated electrodes. This affords a convenient method of measuring very high pressures, and tables have been prepared by various investigators to show the voltages corresponding to various sparking distances. For a given voltage the spark gap is greater between needle points than between spherical electrodes (roughly four times as great between needles as between spheres of 6 ins. diameter for pressures between 40 000 and 80 000 V, R.M.S.). The break-down voltage increases about 0·25 % per 1 mm. rise in barometric pressure, and decreases about 0·35 % per 1° C. rise in temperature; the humidity and amount of dust in the air also affect the break-down voltage very considerably. In X-ray work and insulation tests the crest voltage (§ 30) is important and tables are available * showing the peak voltage corresponding to various gap lengths. For industrial purposes, where sinusoidal waves are used, it is more convenient to use tables showing the R.M.S. voltages for various gap lengths.† With spheres 1 ft. or more in diameter the break-down voltage becomes *roughly* proportional to the gap length and is about 20 000 V per cm. for gaps from 2-5 cm., and about 16 000 V per cm. for gaps from 10-15 cm. (R.M.S. values). These figures are for general guidance only; see B.E.S.A. tables (*loc. cit.*) for complete data.

It is necessary to distinguish carefully between the true dielectric strength of air in volts per cm. when subject to a uniform electrostatic stress, and the break-down voltage for a particular gap. The relation between applied P.D. and maximum dielectric stress is easily calculated where spherical electrodes are used; Russell ‡ gives the formula $R_{max.} = (V / x)f$; where $R_{max.}$ = maximum electric stress in volts per cm.; V = P.D. between spheres; x = minimum distance between spheres, in cm.; f = a correction factor varying with x / a, where a = radius of each sphere, in cm. Tables of values for f are given *loc. cit.* With infinitely large spheres ($x / a = 0$) $f = 1$; for x / a = 0·3, 0·5, 0·7, 1·0, and 1·5, f = 1·10, 1·17, 1·25, 1·36, and 1·56 respectively. Russell ‡ finds that the maximum stress between spherical electrodes in air at the moment of break-down is, in maximum (*not* R.M.S.) kilovolts per cm., $R_{max.} = 27{\cdot}4 + 14{\cdot}1 / \sqrt{a}$, for values of a (= radius of sphere in cm.) from 0·25 cm. to 25 cm. and at 25° C. and 760 mm. barometer. The corresponding maximum (*not* R.M.S.) sparking voltage is calculated from: $V = R_{max.}(x / f)$. This indicates that, *at atmospheric pressure*, the dielectric strength of air is about 27 500 V (max.) per cm., the other term in the expression

* See *X-Rays* by Kaye (Longmans).

† A table of sparking distances for sphere spark gaps from 10 000-400 000 V (R.M.S.) is given in B.E.S.A. Report 137.

‡ *Phil. Mag.*, 6, Vol. 2, p. 258; *Jour. I.E.E.*, Vol. 40, p. 6; *Electric Cables and Networks* (Constable), p. 243.

for $R_{max.}$ being a correction for the effects of currents of electrified air and vanishing when a is very large.

As regards *compressed air*, Watson * finds that the dielectric strength of air at 17° C. is approximately (20 + 25·6 P) kV per cm. (maximum, *not* R.M.S. volts), where P = air pressure in atmospheres absolute. This formula is purely empirical, but is sufficiently accurate for all pressures between 3 and 15 atmos. absolute. Air at 200 lbs. per sq. in. gauge pressure (14·6 atmos. absolute) has a dielectric strength of about 395 kV per cm. (1 000 V per mil), which is about ten times the dielectric strength of air at atmospheric pressure (between 1 in. spheres), and equal to that of micanite.

79. Effect of Air Films in Layered Insulation.—Air films afford an opportunity for hygroscopic insulating materials to become damp; also, the dielectric strength of air at atmospheric pressure is lower than that of solid and impregnating insulating materials. The most serious result, however, of air films between layers of paper, micanite, etc., in insulation subjected to high voltage, is the uneven voltage gradient thus established. The layers of solid insulation and air amount to condensers in series, and the total voltage across the insulation as a whole is divided between the layers in proportion to their thickness and in inverse proportion to their specific inductivity capacity (§ 46). The specific inductive capacity of air being lower than that of solid dielectrics (Table 7), the voltage across an air film is higher than that across an equal thickness of the solid dielectric and may be sufficient to cause break-down; even if break-down does not occur at once the air is ionised, and the solid dielectric is deteriorated by the ozone and nitrous oxides formed.

Example.—Suppose that two 2 mm. sheets of micanite with a 0·1 mm. air film between them be subjected to a P.D. of 6 600 V. Let the P.D. across the micanite be v_m and that across the air be v_a. Denoting the corresponding thicknesses by t_m, t_a; and the specific inductive capacities by k_m, k_a respectively, $vm : va = (t_m / k_m) : (t_a / k_a)$. Now $k_a = 1{\cdot}0$ and $k_m = 6$ (say). Hence, $v_m : v_a = (4 / 6) : (0{\cdot}1 / 1)$; whence $v_m = v_a \times 4 / 0{\cdot}6 = 6{\cdot}7\, va$. But $v_m + v_a = 6\,600$ V; therefore $6{\cdot}7\, v_a + v_a = 6\,600$ and $v_a = 6\,600 / 7{\cdot}7 = 860$ V. A P.D. of 860 V across a 0·1 mm. film corresponds to 86 000 V per cm. which stress is two or three times the dielectric strength of air at normal pressure (§ 78). The air film will therefore break down, and the heat from this discharge will soon cause the micanite to fail.

Due to the excessive stress otherwise placed upon air between layers of paper or fibres of cotton, silk, etc., such materials must be impregnated when used as high-tension insulation, apart from the equally important consideration of excluding moisture.

* *Jour. I.E.E.*, Vol. 43, p. 113.

80. Temperature Limits for Insulating Materials.—As stated in §§ 71, 72, the specific resistance and dielectric strength of all insulating materials decrease rapidly when the temperature is raised. Also, organic insulating materials suffer permanent injury (by charring, becoming brittle, etc.) if heated above a quite moderate temperature (usually in the neighbourhood of 100°-130° C.* For these reasons it is necessary to avoid overheating such materials both during manufacture and in service. If charring occurs the material is converted more or less completely to carbon which is a conductor. Refractory insulating materials used in heaters and the like have necessarily to be exposed to high temperatures, and the approximate limits have been stated in preceding sections relating to the materials concerned. The I.E.C. Rules for Electrical Machinery (Publication No. 34) stipulate that the highest observable temperatures in the machinery covered by these rules † shall not exceed for—cotton, paper, or silk 80° C. when not impregnated, and 95° C. when impregnated or immersed in oil; enamelled wire, 95° C.; mica, asbestos, glass, porcelain, micanite, and similar compositions, 115° C. The proposed temperature limit for oil, measured by thermometer, is 90° C. (*See also* § 136.)

MAGNETIC MATERIALS AND NON-MAGNETIC STEELS.

81. Magnetisation Curve and Cycle.—A solenoid of IT/l ampere-turns per cm. (§§ 42, 43) produces within itself a magnetic field $H = (4\pi/10) \times (IT/l)$ lines per sq. cm. but if the solenoid have a magnetic core, the magnetic induction, B, therein is greater than the magnetising field, H, in the ratio $B/H = \mu$, the permeability of the core material (§ 43). Referring to Fig. 12 the induction rises comparatively slowly from O to a while the initial resistance of the steel to magnetisation is being overcome. From a to A the induction increases rapidly as the field H increases,

* Charring temperatures of insulating materials quoted by Messrs. Pinchin, Johnson & Co. Ltd. are (in °C.): Cambric, shellacked 160°, untreated 168°; oiled duck, 170°-175°; drilling, untreated, 175°; leather, oiled, 182°; silk, oiled, 200°, untreated, 220°; surgical brand cotton, 230°; glazed pressboard, 240°-250°; fine linen, 250°.

† *i.e.* rotating machines of which the terminal pressure does not exceed 5 000 V or of which the rated output does not exceed 750 kVA, or of which the stator cores do not exceed 50 cm. axial length, and all transformers which are not water cooled.

the permeability being high. Beyond *A* the effect of magnetic saturation becomes evident, and at *C* the steel is practically saturated, further increase in the magnetising field producing only the same additional induction as would be produced with an air core; at very high values of *H* (beyond the range of ordinary practice) the induction *OC′* is a negligibly small fraction of the total induction, *i.e.* the permeability of the core is then nearly unity. Within the practical range of magnetising forces, however, the permeability is high—of the order 1 000 at flux densities about 10 000 lines per sq. cm., in the case of those grades of iron and steel which are used as cores for electromagnets, armatures, trans-

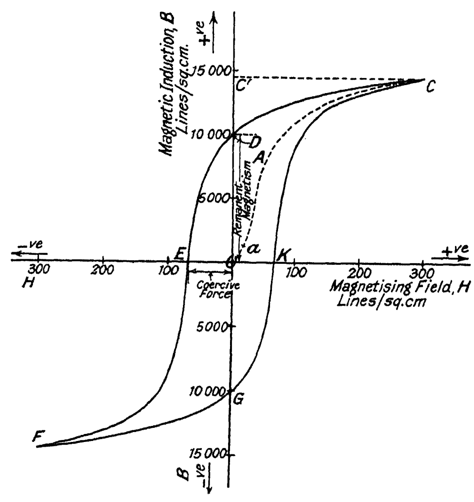


FIG. 12.—Magnetisation curve and cycle.

formers, etc. For such applications high permeability and low hysteresis and eddy current losses (§§ 34, 39) are primary requirements. In permanent magnets, however, the principal requirements are: (i) a high saturation density (*OC′*, Fig. 12); (ii) a high remanent magnetism (*OD*, Fig. 12) when the magnetising force is removed; and (iii) a high coercive force (*OE*, Fig. 12), this being the *negative* magnetising force required to neutralise the remanent magnetism *OD* and thus a measure of the tenacity with which the material holds this remanent magnetism. If the negative magnetising force be increased beyond the value *OE*, the steel is re-magnetised (in the opposite polarity) and ultimately

reaches a saturation point F corresponding to C. On again reducing the magnetising force there is left remanent magnetism OG ($= OD$) to remove which the coercive force OK ($= OE$) must be applied. Beyond K positive magnetisation occurs along the curve KC and *not* along OAC. The latter curve is followed only during the initial magnetisation from the non-magnetised state represented by O; to retrace OAC, we should have to remove the negative magnetising force at such a point on the curve EF that the remanent magnetism was zero (instead of OG). The complete curve $CEFKC$ is the 'hysteresis loop' for the material and the area enclosed by this loop represents the energy expended in overcoming hysteresis during one complete cycle of magnetisation. The loop shown in Fig. 12 refers to Firth's permanent magnet steel. The area of the loop is large, *i.e.* the hysteresis loss is high, but this is inevitably so where a permanent magnet is concerned and is, indeed, an index of merit for the desirable qualities are high remanence and high coercive force both of which involve a wide loop.

Where iron or steel is to be used as the core of an electromagnet, armature, transformer, etc., the desirable qualities include high permeability and a small hysteresis loop.

The succeeding paragraphs deal briefly with core materials, permanent magnet steels, and non-magnetic irons and steels. Typical magnetisation curves for irons and steels and for nickel and cobalt (the only two non-ferrous materials possessing any high degree of magnetic susceptibility) are given in Fig. 13. Permeability values may be obtained for any particular value of induction, B, by dividing the latter by the corresponding value of H. A scale of ampere-turns per cm. is added below the H-scale, this being more convenient for purposes of design (§ 43).

82. Core Materials.—Broadly speaking, maximum physical hardness coincides with the best magnetic qualities (high remanence and coercivity) in permanent magnets whilst physical softness is associated with high saturation density, high permeability and low hysteresis loss, these being desirable characteristics in iron which is to be used in electromagnets (including armature and transformer cores, etc.). For the frames of D.C. motors and dynamos, which serve also as the magnetic yoke between the field poles, cast iron or cast steel is generally employed. Cast steel has the advantage of being mechanically and magnetically

superior to cast iron; also, it is magnetically equal to or better than wrought iron and is more convenient for the constructional purposes concerned. A 3 % nickel steel is sometimes used for the frames and rotors of large dynamos on account of its excellent mechanical properties. In the rotating field systems of high-speed turbine-driven machines the mechanical stresses are such that rolled steel plates offer advantages compared with forgings (§ 145).

Where the magnetic field is alternating—as in armatures, transformers and the field-systems of A.C. motors—it is necessary to subdivide the core into thin sheets in order to reduce the eddy current loss (§ 39). For the same reason it is desirable that the electrical resistance of the metal should be high. The dimensions of such cores have a large influence on the overall dimensions and cost of the machine or transformer and, in order to reduce them, high permeability and high saturation density are required. The shape of the curves in Fig. 13 is such that a small vertical distance between them involves a large increase in ampere-turns per cm. in order to reach a given flux density in the inferior material.

For many years sheets of Swedish charcoal iron were the best material available for cores; these have a maximum permeability, 3 000; a hysteresis loss about 1·8 W per kg. * ($B_{max.}$ 10 000 gauss); and an electrical resistance, 10 microhms per cm. cube. It has been found, however, that a small percentage of aluminium or silicon greatly increases the permeability and reduces the hysteresis loss of iron. The authors are indebted to Messrs. J. Lysaght, Ltd., and J. Sankey & Sons, Ltd., for permission to reproduce the curves in Fig. 13, relating to their special electrical steels 'Lohys,' 'Special Lohys,' and 'Medium Resistance' dynamo steels, and 'Stalloy' which is a high resistance silicon steel used mainly in transformers. The total hysteresis plus eddy loss in 20 mil sheets of these materials at $B_{max.} = 10\ 000$ gauss, 50 cycles per sec. is approximately 3·5 W per kg. for Lohys (sp. gr. 7·8); 2·9 W per kg. for Special Lohys (sp. gr. 7·8); 2·5 W per kg. for Medium Resistance Steel (sp. gr. 7·75); and 1·75 W per kg. for Stalloy (sp. gr. 7·5). The maxi-

* 1 watt per kg. = 1 550 ergs per cu. cm. per cycle, at 50 cycles per sec. (nearly).

mum permeability of 4 % silicon steel is nearly 8 000, and an important advantage of this material is that the 'ageing' is negative, *i.e.* the losses actually decrease during years of service.

An iron alloy containing 35 % of cobalt has a saturation density about 25 % higher than that of iron, but this alloy is prohibitively expensive at present; for hard cobalt steel *see* § 83.

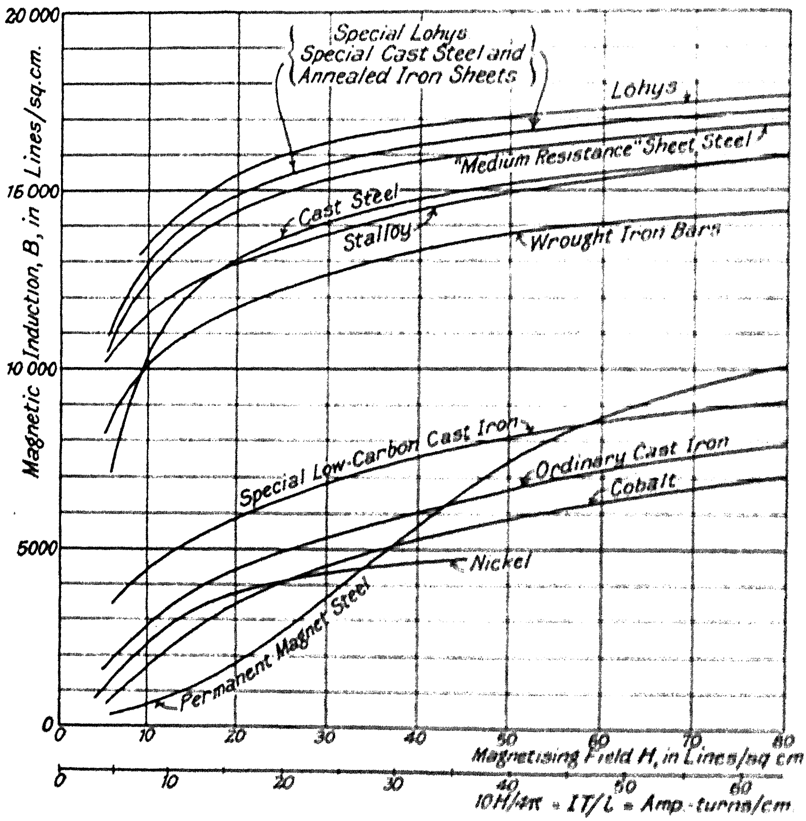


FIG. 13.—Magnetisation curves for various materials.

Electrolytic (carbon-free) iron melted *in vacuo* and thus freed from oxygen has a maximum permeability of nearly 20 000, a hysteresis loss about 0·5 W per kg. (B_{max}, 10 000 gauss, 50 cycles per sec.), and an electrical resistance about 10 microhms per cm. cube. Swedish iron similarly treated is deprived of its carbon and gives nearly as good results. Yensen's tests on

vacuum-melted 3·4 °/$_{o}$ silicon alloy show this material to ha maximum permeability between 60 000 and 70 000; hysteres loss about 0·2 W per kg. ($B_{max.}$ 10 000 gauss, 50 cycles); ar electrical resistance nearly 50 microhms per cm. cube. There a obvious practical difficulties in melting large quantities of met *in vacuo*, but the use of this class of material is likely to exten

Large quantities of powdered iron are used in the Unit States as a substitute for hard iron wire in the cores of 'loading coils for telephone circuits, where the requirements are constai permeability and small loss by hysteresis and eddy current Electrolytic iron is ground to pass a sieve with 100-200 mesh per inch, rolled with flake zinc (which is then removed), insulate with shellac, and compressed at 100 tons per sq. in. to produ blocks nearly as dense as iron and with a tensile strength of to ½ ton per sq. in. A permeability of 50 to 150 is obtained i the range $H = 25$ to 50 gauss (*cf.* Fig. 13), the permeability particular samples being nearly constant over a considerable rang of flux density. The eddy losses are low, due to the iron bein electrically discontinuous.

'Permalloy' is the generic name applied to nickel-iron alloy containing about 80°/$_{o}$ Ni and 20°/$_{o}$ Fe. These alloys possess r markable magnetic properties; they will certainly be of impo tance in electrical communication (telegraphy, etc.) and may fin application in heavy engineering. When properly heat-treate permalloy has an 'initial permeability' (*i.e.* permeability at zer field, by extrapolation) as high as 13 000, or more than thirty time that of the best soft iron. Permalloy, although it has a saturatio value B = 11 000 gauss (approx.), comparable with that of iron approaches saturation in the earth's field. The area of th hysteresis loop for permalloy, with $B_{max.} = 5\,000$ gauss, is one sixteenth of that for soft iron. For B = 4 000 to 6 000 gauss th permeability of permalloy is 80 000 to 90 000, which is very muc higher than the value for silicon steel (§ 82). For further informa tion, see *Jour. Franklin Inst.*, Vol. 195, p. 621.

83. Permanent Magnet Steels.—As explained in § 81 tw of the main requirements in a permanent magnet steel are hig remanence and high coercivity; in addition the magnet shoul not be weakened appreciably by 'ageing' when exposed to vi bration, temperature variations, etc. High-carbon steel (1 t 1½ °/$_{o}$ carbon) can be used for permanent magnets, best result

being obtained when the metal is so quenched as to yield the finest grain and greatest mechanical hardness; a remanence of 8 500 gauss and a coercivity of 50 can be obtained. Alloy steels are now available which give far better magnets than plain carbon steel, but in the alloys there are many factors determining the magnetic qualities, and it does not follow that the latter are best when the metal is in its hardest state.

Most of the permanent magnet steels on the market are tungsten alloys containing from $5\frac{1}{2}$ to $6\frac{1}{2}$ % tungsten; 0·55 to 0·7 % carbon; 0·3 to 0·5 % manganese; 0·1 to 0·15 % silicon; and traces of phosphorus and sulphur. When quenched at 825°-850° C. such steel has a remanence of 9 000 to 11 000 gauss and a coercivity of 60 to 70 gauss. Chromium steel containing about 2 % chromium and 0·85 % carbon gives about the same coercivity as tungsten steels, but the remanence is lower (9 000-9 500). Honda's cobalt steel, containing 35 % cobalt, 7 to 9 % tungsten, and 0·5 % carbon, can be made to give a coercivity of 180-200. Hadfield's 'Permanite,' also a cobalt steel, is claimed to have a remanence of 11 200 and a coercivity of 120 gauss.

All permanent magnets should be 'aged' by heating them to 100° C. for 24-48 hrs. and subjecting them to vibration. The extent and rate of ageing in service depends considerably upon the form of the magnet.

84. Non-Magnetic Steels.—Iron loses its magnetic properties completely when (and whilst) heated to the temperature of recalescence (about 680° C.) or higher. This is important in connection with the use of lifting magnets (Chapter 31) and in the magnetic determination of the correct temperature for hardening carbon steel (§ 122). A somewhat similar phenomenon is observable in 25 % nickel steel which is normally non-magnetic, but which becomes magnetic when cooled to − 40° C. and then remains magnetic until heated to 600° C. Steels which are non-magnetic at atmospheric temperature are useful for structural purposes where the mechanical strength of steel is desired without the disturbing effects which would be caused in the neighbourhood if magnetic material were employed. About 16 % or less of manganese (according to the amount of carbon present) produces a non-magnetic steel, the electrical resistance of which is

* 'Permanent Magnets in Theory and Practice,' by S. Evershed, *Jour. I.E.E.*, Vol. 58, pp. 780 *et seq.*, is a classic treatment of the subject.

about five times that of iron. Hadfield's manganese steel containing 13 °/。 manganese, 1·3 °/。 carbon, and 0·3 °/。 silicon is practically non-magnetic, and is used near magnetic compasses and in other similar applications; the metal is practically unmachinable and, indeed, owes its principal applications (to special trackwork, rock-crushers, etc.) to its remarkable toughness and strength.

A non-magnetic cast iron 'No-Mag' (Dawson-Ferranti patent application 33290/20) is recommended for use in resistance grids, switch, and transformer covers, and general structural components in which eddy currents are to be avoided. This material resembles ordinary cast iron except that it is tougher, more malleable, and of higher electrical resistance (140 microhms per cm. cube); its permeability is 1·02-1·03.

Refractory Materials and Timber Preservatives.

85. Refractory Materials.—Information concerning the heat-resisting properties of porcelain, asbestos-compositions, and other materials which are used primarily as electrical insulators, is given in earlier paragraphs. The materials here considered are those used as supports for the hot wires of heating apparatus, as linings for electric furnaces, and in other applications where resistance to heat is a primary consideration. Another requirement is low thermal conductivity, in order that heat losses may be reduced. At their working temperature, most refractory bricks, etc., become relatively good electrolytic conductors (§ 68), hence they must not be subjected to high P.D. Mechanical strength and low temperature coefficient of expansion are desirable from the constructional point of view. Chemical inertness, particularly resistance to oxidation, is essential.

Under suitable conditions the electric furnace can be made to melt practically all materials, hence it is correspondingly difficult to obtain refractories able to resist for a reasonable period the high temperatures attained, the chemical action of the charge, and the scouring action of the molten metal; no known material will stand up to these conditions indefinitely. The mechanical strength of all refractories is low at high temperatures and the melting (or flowing) temperature is reduced by 10 to 15 °/。 by the application of a load of 50 lb. per sq. in. Conditions are much less severe in furnaces for the common non-ferrous metals, because not only

are the melting-points of the latter lower than that of steel, but also there is not, in simple melting, the severe slag action which is inevitable in steel refining.

Refractory materials may be calcined, ground, mixed with binder, and then either formed into bricks, or rammed to form a solid hearth or lining. The initial drying and heating must be conducted slowly and uniformly. Moisture in refractories containing lime is apt to cause slaking. Freezing is disastrous to most refractories.

Refractories with a *basic* reaction are: alundum, bauxite, carborundum, dolomite, magnesite, and zirconite; those with an *acid* reaction are silica and kieselguhr; and those which are *neutral* are chromite and fireclay. Brief notes on these materials are appended:—

Alundum (artificial corundum) is made by fusing and refining bauxite in the electric furnace. Its thermal conductivity is about 20 % higher than that of silica. Linear coefficient of expansion 8×10^{-6} per 1° C. Specific resistance 9×10^3 Ω per cm. cube at 20° C.; 190 Ω per cm. cube at 1 600° C. Strong at high temperatures, less liable than silica to spall or splinter. Used in heating and cooking apparatus and for furnace roofs. Weakened by lime and magnesia vapours. Melting-point, 2 000°-2 100° C.

Bauxite Brick consists of calcined alumina with fireclay bond, fired at the highest attainable temperature in order to complete shrinkage. Melting point 1 550°-1 800° C. according to quality.

Carborundum (silicon carbide or crystolon) is useful for furnace roofs, due to its refractory nature, its strength at high temperatures, its high thermal conductivity (more than twice that of silica), and its low coefficient of expansion (lower than that of silica). It can be used at temperatures exceeding 1 800° C. So-called ***carbon bricks*** consist of carborundum.

Chromite Brick containing about 40 % chromium oxide together with alumina, silica, and iron oxide is attacked by molten steel and weakens about 1 550° C. Melting-point about 2 100° C.

Dolomite consists of limestone with a high percentage of magnesia. When calcined and mixed with tar it is used for rammed hearths of steel furnaces. If exposed to moisture the lime slakes; for this reason dolomite bricks are rarely used.

Fireclay is a generic term applied to clays which melt about 1 550-1 750° C. The principal constituents are 25-35 % of alumina and 50-60 % of silica. ***Firebricks*** made from burnt fireclay with raw clay as bond, are not suitable for exposure to the full heat of electric furnaces, but are useful as heat insulation. Specific heat, 0·22-0·30 at temperatures from 500°-1 500° C.; weight, 130 lbs. per cu. ft.; crushing strength 1 300 lbs. per sq. in. at 1 350° C., softens about 1 550° C. Thermal conductivity, 10-15 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness.

Kieselguhr (diatomaceous earth) contains up to 95 % silica and consists of the shells of diatoms. Due to the innumerable air pockets (of microscopic proportions) in the material—whether used as a loose powder or in the form of bricks—the

thermal conductivity is very low (from 1 to 2 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness, *i.e.* about one-tenth that of solid silica). Kieselguhr is useful for lagging, and can be used in building and lining high temperature furnaces. Owing to the enclosed air, the apparent sp. gr. is about 1·0. Melting-point about 1 610° C.

Magnesite is used with tar for rammed hearths, etc., or calcined magnesite (85 °/₀ to 94 °/₀ magnesium oxide) is moulded without bond to form bricks which are fired at or above 1 700° C. to complete their shrinkage. Pure magnesia melts at about 2800° C. and magnesite brick at 2 165° C. Magnesite is much used for the hearths and walls of steel furnaces and in furnaces for melting aluminium and its alloys, bronze, bearing metals, lead, and copper. *Magnesite bricks* expand greatly with temperature ($\frac{3}{16}$ in. per ft. should be allowed at expansion joints), and though the melting-point is high the bricks are weak at a much lower temperature. Crushing strength 65 lbs. per sq. in. at 1 650° C.; weight 164 lbs. per cu. ft.; thermal conductivity 15-20 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness.

Silica Bricks (Dinas bricks) are made from sharp quartzite with 2 °/₀ lime as bond; the bricks should be at least 96 °/₀ silica. They are strong at high temperatures but spall if subjected to sudden temperature changes. They are used for furnace roofs and as lining in furnaces for melting bronze, copper, or silver. Silica is liable to attack by fluxes. Specific heat 0·22-0·30 between 500 and 1 000° C.; weight 100-110 lbs. per cu. ft.; crushing strength 1 850 lb. per sq. in. at 1 350° C. and over 75 lbs. per sq. in. at 1 500° C.; thermal conductivity 5-10 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness. Melting-point 1 700° C. *Ganister brick* is made from siliceous rock containing about 10 °/₀ of clay and requiring no other bond. *Pure silica* (quartz) flows at 1 750° C. and is used in heating and cooking apparatus, etc. (§ 74, II (*b*).

Zirconia, which is now available in commercial quantities, is exceptionally refractory (melting-point, 2 600°-3 000° C.) and may be used with tar for rammed linings or in the form of bricks. Though dearer than magnesite, the maintenance costs are low because zirconia is very resistant to slags and metals, is mechanically strong, and has low expansion and low thermal conductivity. The specific heat is 0·14-0·18 from 500°-1 500° C. Zirconia bricks withstand 1 800° C. satisfactorily; iron oxide, as impurity, lowers the melting-point.

Refractory cements are generally of the same composition as the mixture from which the bricks are baked. A paste of asbestos (2 parts) and water glass (3 parts) mixed with water is useful in repairing refractories exposed to moderate temperatures.

86. Preservative Processes for Timber.—Wood impregnated with paraffin wax is acid-resisting and moisture-proof, but this treatment is too expensive for use in the wholesale preservation of timber (particularly poles for overhead lines, § 323) which is to be exposed to weather or buried in the ground. The preservative processes applicable in such cases may require extensive plant for the injection of antiseptic solution under pressure, or penetration may be secured by more or less prolonged immersion in open tanks. Among the pressure processes are creosoting by the old method or the modern Rüping and Rütger processes. A large number of the patent solutions have been introduced for open-tank processes.

Creosote is the preservative most used for poles in this country. To facilitate penetration small radial holes may be forced (*not* drilled) in the butt. It is advisable to impregnate the whole pole and not merely the butt. There is a certain settlement and oozing out of the creosote in service; after a time there is about one-third the original weight of creosote in the butt and a less proportion in the upper parts. Weight for weight, creosote is estimated to have about twice the antiseptic effect of copper sulphate at one-fiftieth the cost for materials. With deep penetration the oil is fairly resistant to attack by white ants. Injection of about 10 lbs. of creosote per cu. ft. of timber is recommended for poles, and the wood should not be cut or drilled after creosoting, as the heavier fractions of the oil lie near the surface.

Kyanising is a low-pressure process, seasoned timber being steeped for days or weeks in a weak solution of mercury chloride (corrosive sublimate). The solution does not penetrate deeply, and the weight of salt absorbed is given as about 0·01 lb. per sq. ft. of surface for fir. The preservative is said to be leached out by rain, and may then contaminate drinking water, but the process has been used extensively on the Continent. Kyanised timber can be painted.

Aczol is a mixture of copper or zinc ammoniates with an antiseptic acid containing phenols and naphthalenes. Its action is to cement together the surface layers of wood fibres and tissues, and is claimed to be as effective as creosoting, and to cost about 2½d. per cu. ft. for pole timber.

The Powell *saccharine* process employs by-products of sugar-refining which are said to form an approximation to amorphous wood in the interstices of the timber treated. Wood is appreciably strengthened by the treatment, and, by inclusion of arsenic in the solution, becomes resistant to white ants. The process is used fairly extensively in Australia, New Zealand, and India. Treated timber is clean, dry, and can be painted.

Solignum has proved useful within the author's experience when merely painted on. *Microsol* consists of sulphates of copper, soda, and lime. *Bellit* consists mainly of sodium fluorite. There are many other materials and processes which cannot be dealt with here. Treatment by simple metallic salts is not in high favour in this country.

An exhaustive treatment of the nature of decay in wood, and of preservative materials and processes, is given by A. J. Wallis-Tayler in the Royal Society of Arts *Journal*, Vol. 62, pp. 286 *et seq.* A valuable monograph on the antiseptic treatment of timber is given by R. S. Pearson in *Indian Forest Records*, 3, Part 2, and a bibliography is given therein.

Data concerning the life of timber, treated and untreated, are given in § 323.

87. Bibliography (*see* explanatory note, § 58).

STANDARDISATION REPORTS, ETC.

(1) *I.E.C. Publications.*

No. 28. International Standard of Resistance for Copper.

No. 34. Rules for Electrical Machinery.

(2) *B.E.S.A. Reports.*

No. 7. Insulated Annealed Copper Conductors for Electric Power and Light.

No. 55. Hard Drawn Copper and Bronze Wire.

No. 68. Method of Specifying the Resistance of Steel Conductor Rails.
No. 72. British Standardisation Rules for Electrical Machinery.
No. 115. Specification for Metallic Resistance Materials.
No. 128. Specification for Bare Annealed Copper Wire for Electrical Machinery and Apparatus.
No. 134. Specification for Steel Poles for Telegraph and Telephone Lines.
No. 137. Specification for Porcelain Insulators for Transmission Lines.
No. 139. Specification for Red Fir Wood Poles for Telegraph and Telephone Lines.
No. 144. Specification for Creosote for the Preservation of Timber.
No. 148. Specification for Insulating Oils for Use in Transformers, Oil Switches, and Circuit Breakers.
See also Specifications for various railway and rolling stock materials, Chapter 35, Bibliography.

BOOKS.

Asbestos. A. L. Summers (Pitman).
Electrical Insulation. W. S. Flight (Pitman).
Special Steels. T. H. Burnham (Pitman).
Magnetic Induction in Iron and other Metals. J. A. Ewing ('Electrician').
Industrial Chemistry. H. K. Benson (Macmillan).
Insulation and Design of Electrical Windings. A. P. M. Fleming and R. Johnson (Longmans).
Mechanical Technology. G. F. Charnock (Constable).

I.E.E. PAPERS.

Switch and Transformer Oils (Sub-Committee Report). Vol. 53, p. 146.
Insulating Oils (Sub-Committee Report on Tests on Transformer Oils). Vol. 54, p. 497.
Moulded Insulating Compositions, R. T. Fleming. Vol. 57, Supp. Part 2, p. 322.
Carbon Brushes: Considered in Relation to the Design and Operation of Electrical Machinery, P. Hunter-Brown. Vol. 57, p. 193.
Properties and Characteristics of Insulating Materials, R. T. Fleming. Vol. 60, p. 58.
Effect of Heat on the Electric Strength of Some Commercial Insulating Materials, W. S. Flight. Vol. 60, p. 218.
Properties and Uses of Micas (Report from B.E.R.A.). Vol. 60, p. 339.

MISCELLANEOUS.

Reports on materials by the B.E.R.A. are published in the I.E.E. Journal.
Tests on Insulating Varnishes, W. S. Flight. El. Rev. Vol. 89, p. 771.
Dielectric Strength of Solid Insulating Materials, W. S. Flight. Vol. 90, p. 40.
For Bibliographies on Dielectrics, including references to the principal articles on the subject in periodical literature, *see* E. H. Rayner, Jour. I.E.E., Vol. 49, p. 53, and D. M. Simons, Jour. Amer. I.E.E., Vol. 41, p. 617.
Magnet Steels, J. F. Kayser. Electrn., May 25, 1923, p. 557.
Cobalt Steel for Magnets, J. F. Kayser. Engineer, Vol. 135, pp. 57, 83.

CHAPTER 3.

INSTRUMENTS AND MEASUREMENTS.

88. Measurements Required.—In order to know what is happening in an electrical circuit it is necessary to measure the quantities, current, pressure, power, frequency, etc., relating to the current itself. Also by utilising properties of the electric current or variations in electrical quantities produced by other than electrical causes it is possible to measure the latter; for instance, the resistance of a conductor varies with temperature and may be used to measure temperature (§§ 61, 122). Instruments for measuring electrical quantities, and electrical instruments for measuring other than electrical quantities, are described in this chapter, mainly as regards the principles upon which they operate and the facts bearing upon their use. For details of construction reference must be made to books devoted to this subject (§ 125).

89. Types of Instruments.—An electric current can be measured by any of the effects which it produces, and, in so far as the effects of direct and alternating current are different, some instruments can be used only for direct current and others only for alternating current measurements. In general—

(*a*) Any 'polarised' instrument the direction of deflection (or other action) of which reverses with the direction of the current is unsuitable for alternating currents unless, as in the oscillograph (§ 118), the instrument is capable of following the alternations completely and accurately. Polarised instruments can be arranged with a centre-zero scale so as to read in either direction without reconnection.

(*b*) Instruments in which the effect varies with the square of applied current or P.D., or with the product of suitably related currents or P.D.'s, are unaffected by alternations in these quantities (except as regards hysteresis and eddy current effects, §§ 34, 39, 100, 101, *b*) and can therefore be used in A.C. circuits. They cannot be arranged as centre-zero instruments.

(c) Instruments which depend upon alternation of current for their action (e.g. induction ammeters, § 102) cannot be used on D.C. circuits.

The effects of the electric current on which its measurement may be based, and the main types of instruments utilising these effects are as follows:—

(i) *Electro-Chemical.*—The electrolytic effect of a direct current is made the basis of the international definition of the ampere (§ 3). It cannot be used to measure an alternating current because the electrolytic effect of one half-cycle is reversed and neutralised more or less completely by the ensuing, reversed half-cycle (see, however, Chap. 17). Neither can the electrolytic effect be used to measure the instantaneous value of a varying direct current. The amount of electro-chemical action produced varies with the *quantity* of electricity (§ 28), hence this effect is used to measure ampere-hours (§114) or, on the assumption of an unvarying current (§ 3), amperes indirectly.

(ii) *Thermal.*—The heating effect of an electric current varies with the square of the current (§ 49), and is therefore the same for A.C. as for D.C. The expansion of a fine wire traversed by the current to be measured is made to produce a convenient deflection by means of a mechanical or optical magnifying system (§ 99). Alternatively the heating of a special resistance element may be measured by a thermo-couple built permanently in the circuit of a moving coil instrument (§ 99).

(iii) *Electromagnetic.*—Instruments of this type are used for practically all ordinary commercial measurements. A current-carrying conductor establishes round itself a magnetic field (§ 32) which can be used: (a) to attract or displace a permanent magnet (as in certain galvanometers, § 96) or a piece of soft iron (as in 'moving iron' instruments, § 100); (b) to react with the field of a permanent magnet (as in 'moving coil' instruments, § 101 a) or with the field of a second current-carrying conductor (as in dynamometer instruments, § 101 b); or (c), if alternating, to induce currents in a second conductor and then to react with the field of the latter (as in induction instruments, § 102). The general principle employed is that of attraction or repulsion between fixed and moving parts, one of which is a current-carrying conductor (usually wound in the form of a coil in order to multiply its effect, § 42). The moving part—whether a permanent

magnet, soft iron, or a coil of wire—tends to deflect against the control of a constant magnetic field, a spring, or the force of gravity as the case may be. The deflection or the controlling force required to prevent deflection of the moving system is a measure of the quantity under investigation. Polarised electromagnetic instruments, *i.e.* those employing permanent magnets, cannot be used for A.C. measurements (excepting oscillographs, § 118, and vibration galvanometers, § 96), but moving (soft) iron instruments and dynamometer instruments can be used on A.C. circuits. Induction instruments cannot be used on D.C. circuits.

Moving iron and moving coil instruments will withstand much greater overload than hot-wire instruments. The hot wire of the latter is necessarily relatively thin and worked at high temperature, and the heating varies with the square of the current; on overload the hot wire is liable to be melted sooner than a protective fuse-wire in series with it.

(iv) *Electrostatic.*—The electrostatic attraction between two metallic vanes connected between points at different potential may be used to measure this P.D. The only current flowing in the instrument circuit is the extremely small charging current (§ 46) required to charge the condenser formed by the vanes of the instrument; this may be neglected for all practical purposes. Electrostatic instruments are equally suitable for measuring continuous or alternating pressures. They can be used to measure current (D.C. or A.C.) indirectly by measuring the P.D. across a non-inductive resistance traversed by the current in question (§ 107 *c*); for economic reasons, however, the P.D. across resistance in the main circuit must be kept low and electrostatic instruments are not suitable for the measurement of small P.D.'s. The principal uses of electrostatic instruments are for pressure measurements in laboratory work, and in high-tension circuits (§ 103). Electrostatic instruments depending upon the repulsion between similarly charged vanes are used to indicate whether conductors are 'live' (§ 104). In damp places leakage current affects the reading of any electrostatic instrument.

(v) *Dielectric Break-down.*—The break-down of a dielectric is determined by the *maximum* P.D. to which it is subjected (§ 72) and the length of gap across which sparking occurs between suitable electrodes (§ 105) forms a measure of crest voltage and hence

of R.M.S. voltage if the crest factor (§ 30) of the wave be known. This method is equally applicable to continuous and alternating pressures, but is only suitable for extra high voltages.

90. Control and Damping.—In thermal, electromagnetic and electrostatic instruments a 'deflecting' force is exerted upon a pivoted (or suspended, etc.) 'movement,' deflection of which is resisted by gravity, a spring, or some other 'controlling' force. In some types of laboratory instrument there is an advantage in varying the control (say by varying the torsion of a spring) so as to hold the movement over a zero index mark. The measure of the control force is then a measure of the electrical quantity tending to deflect the movement. For all practical purposes it is much more convenient to use a deflecting instrument, the pointer of which moves over a calibrated scale (§ 91) and comes to rest when the control force is equal and opposite to the deflecting force. If the deflecting force be varied suddenly, by a sudden change in the quantity measured, the momentum of the movement will tend to carry the latter beyond the new position of equilibrium, *i.e.* the pointer will tend to overshoot the correct deflection and oscillate before coming to rest. This may be prevented by applying a retarding force which retards the motion of the movement, but which diminishes as the movement comes to rest and is then zero. Such a 'damping' force is provided by the movement of a vane in a dashpot chamber, the walls of which it just clears; by the motion of a vane, or the 'movement' itself, in oil; or by the eddy currents induced in a brake disc moving between the poles of a permanent magnet. Solid friction, such as produced by a brake band, may *not* be used for damping because it exerts a force when the movement is stationary and thus affects the deflection.

A commercial instrument is said to be 'dead beat' when the oscillations die away rapidly. If the damping be increased till there is no overshooting, the instrument is then strictly 'aperiodic'; further increase of damping makes the instrument 'sluggish,' *i.e.* the pointer crawls slowly to the steady deflection. Oscillographs must be exactly aperiodic or 'critically damped,' but in ordinary indicating instruments a slight degree of overshooting is useful as indicating that there is no abnormal friction. Recording instruments must be aperiodic. Sluggishness produced by over-damping is useful where it is desired to obtain an average

reading of a quantity which is fluctuating too slowly for the movement to take up a mean position by its own inertia.

Gravity-controlled instruments must be levelled before use, and, since the control force varies with the sine of the angle of deflection in this type, the scale is cramped near the zero. Spring-controlled instruments can and should be balanced so that they can be used without levelling; the control exerted by the spring varies uniformly with the deflection and this tends to produce an even scale (§ 91). On the other hand, the spring can, if desired, be 'set up' so that the pointer does not move until a predetermined value of current, etc., is reached; the suppressed portion of the scale may be as much as 0·7 of the maximum reading, the whole scale length being then available for the remaining 0·3 of the maximum (*e.g.* the instrument might indicate 70 to 100 V only). Control springs are used to carry current into moving windings.

Air vane damping is generally employed in moving iron instruments, and eddy current damping in hot wire instruments, moving coil instruments, and supply meters. The time taken for the pointer of an indicating instrument to come to rest should not exceed (0·4 × total length of scale, in inches) seconds.

91. Scales.—When the pointer of any instrument is at rest at any point on its scale the control force is in equilibrium with the deflecting force on the movement *in the position concerned.* By varying the control (§ 90) or the manner in which the deflecting force on the movement varies with the position of the latter, any desired gradation of scale divisions can be obtained within a wide range. For general testing purposes a uniformly divided scale is desirable, but for switchboard service a scale which is open between the usual working limits and contracted elsewhere facilitates observation. Though an open scale contributes to accuracy of reading it has no relation to accuracy of indication (§ 92). The 'effective range' of an ammeter, voltmeter or wattmeter scale is assumed to extend from the maximum scale value down to 10 % of the latter if the scale be nearly uniform and down to 25 % if the scale be greatly contracted near zero; if the scale be partially suppressed (§ 90) the whole actual range is effective.

The value of each scale division should be 1, 2, or 5 of the units measured or a decimal multiple or sub-multiple of these numbers. The angle subtended by 1 scale division should be at least 0·5° in

sub-standard and portable first-grade instruments (§ 92) and at least 1° in other instruments; *see also* B.E.S.A. Report No. 89.

In order that it may all be visible at once, an edge-type scale must not subtend more than 80°. Until recently disc-type moving-iron and moving-coil instruments have been built with scales subtending about 85°. By modifying the mechanical details and placing the scale arc on a diameter of the disc a scale length equal to the diameter of the instrument can be obtained, subtending about 125°. In the Record 'Cirscale' moving-coil instruments (§ 101*a*) the scale subtends 300°-330°.

If two instruments measuring related quantities A, B, be arranged so that their pointers cross (without touching) there is a definite position of the pointer intersection corresponding to every pair of values of A, B and this position—read on a third scale below the crossing pointers—indicates the value of any quantity C which is a definite function of A and B. For instance the pointer-crossing of an ammeter and a voltmeter may be used to indicate the resistance of a D.C. circuit (§ 17). Again, the crossing of wattmeter and ammeter pointers indicates power factor if the voltage be constant (§§ 56, 109-111); and the crossing of the pointers of two wattmeters used to measure power by the two-wattmeter method (§ 110) indicates the power factor of a three-phase load. It is not possible to read the intersection accurately when the pointers are nearly parallel or collinear. (For meter dials, *see* § 113.)

92. Instrument Accuracy and Errors.—The British Engineering Standards Association (Report 89) recognise three grades of instruments, *viz. Sub-standard*, used mostly for checking other instruments, and *First Grade* and *Second Grade* instruments, used on switchboards and as portable instruments where the higher grade of accuracy is not required. The error * in indicating voltmeters of these three grades should not exceed ± 0·2 %, ± 1 %, and ± 2 % respectively. The same limits may be applied to ammeters of the moving coil, permanent magnet type; other indicating ammeters should not exceed ± 0·5 %, ± 2 %, and

---

* Expressed as per cent. of maximum scale value throughout the effective range (§ 91) in the case of sub-standard instruments. In first- and second-grade instruments the error is expressed as per cent. of indication from full scale to middle point, and as per cent. of half the maximum scale value from middle point to lower end of effective range.

± 4 %. The error in the three grades of indicating wattmeter *at unity power factor* (§ 109) should not exceed ± 0·5 %, ± 2·5 % and ± 5 %. All of these figures represent permissible maximum errors; higher accuracy is obtained in present-day practice.

Unless some useful purpose is served by the higher accuracy, it is inadvisable to specify sub-standard or first-grade instruments because they are necessarily more costly and delicate. The accuracy of graphic recording instruments (§ 93) should be between that of first- and that of second-grade indicating instruments. If an instrument must be used with a shunt, instrument transformer, etc. (§§ 107, 108), this auxiliary equipment should be regarded as part of the instrument for purposes of calibration.

Apart from constructional errors due to friction, incorrect calibration, etc., electrical instruments are subject to errors attributable to variation in conditions or quantities other than those measured. The permissible limits for errors due to such causes may be summarised as follows (*see* however B.E.S.A. Reports 89 and 90 for a full statement):—

(i) *Variations in Air Temperature.*—The resistance of copper increases with temperature rise (§ 61) so that in voltmeters and shunted ammeters the current through the instrument tends to decrease as the temperature rises. The actual variation may be reduced by 'swamping' the copper with as much metal of zero temperature coefficient of resistance (*e.g.* manganin) as may be connected in the circuit. In rotating meters where eddy current braking is employed, the increased resistance of the copper or aluminium brake disc at higher temperatures reduces the braking torque. Temperature variations affect more or less the strength of control springs. The net effect of temperature changes varies widely in different instruments, but should always be considered.

The percentage change in indication should not exceed ± 0·1 %, ± 0·2 % and ± 0·4 % per 1° C. change in air temperature, for sub-standard, first, and second grade indicating voltmeters and ammeters respectively. For indicating wattmeters the corresponding limits are ± 0·2 %, ± 0·3 %, and ± 0·4 %.

(ii) *External Magnetic Fields.*—In so far as external magnetic fields affect appreciably the working magnetic field of the instrument they are a potential source of error. In many cases error due to external magnetic field can be eliminated by using the *astatic principle*, *i.e.* duplicating the instrument on a common spindle and arranging the connections so that the torque on one element is increased and on the other decreased by the stray field.

The variation in maximum indication of an indicating or recording ammeter or voltmeter for permanent installation should not exceed 3 % of that indication when the instrument is exposed to a magnetic field of 10 gauss (§ 40) in the direction producing maximum error; in A.C. instruments the disturbing field must be alternating and in phase with that in the coil of the indicator. Sub-standard and portable first-grade instruments should bear a statement of the precautions required with regard to stray fields.

(iii) *Variations in Frequency.*—Between 25 and 100 cycles per sec. inclusive the variation in indication of any A.C. instrument (excepting frequency meters) throughout its effective range (§ 91) should not exceed: For indicating sub-standard instruments $\pm$ 0·25 % of the indication, for 50 % variation in frequency; for first-grade instruments $\pm$ 1 % and for second-grade instruments $\pm$ 2·5 % of the indication for 5 % variation in frequency. (In multirange instruments with lowest volt range below 110 V these limits may be doubled.) The corresponding limit for recording instruments is $\pm$ 2 % of the indication for 5 % variation in frequency.

(iv) *Power Factor.*—The variation in indication of a wattmeter throughout the effective range (§ 91) for variation in P.F. of load from 1·0 to 0·5 should not exceed $\pm$ 0·5 %, $\pm$ 2 %, or $\pm$ 4 % for indicating sub-standard, first- and second-grade instruments respectively, and $\pm$ 3 % for recording wattmeters.

93. **Recording Instruments.**—A graphic recording instrument is essentially an indicating instrument, all the movements of the pointer of which are recorded on paper, either by the pointer itself being used as a pen or by its being used as a type-bar as explained below. The paper is calibrated, in one direction by divisions equal to those of the instrument scale and in the other direction by equally spaced divisions which form a measure of time. The chart may be circular and rotated once in 24 hrs. (or other convenient time) or it may be in the form of a long band which is wound from one drum to another at a speed of say 1 in. per hr. (up to 1 in. per sec. if required). The chart is generally driven by clockwork and the error in its driving should not exceed 5 min. in 24 hrs. (about 0·35 %).

In most cases the pointer is used as a pen. The displacements proportional to the quantity measured are then along the arc of a circle of radius equal to the length of the pointer. The chart movement (proportional to time) is linear in the band-type but angular in the disc-type of record; the latter type in particular is difficult to interpret because the time interval which corresponds to 1 in. circumferential displacement of the chart at 2-in. radius, is represented by 2 ins. at 4-in. radius, and so on. Various methods are available by which a pointer, turning as usual about a centre, can be made to record its position with regard to a fixed straight line perpendicular to the line of advance of the paper. The curve thus traced has rectangular axes of co-ordinates. In one system the pointer normally swings clear of the paper, and an inked ribbon is placed between the two. At predetermined intervals an electromagnetic device presses the pointer on to the ribbon and thus records the deflection by a dot on the paper.

The record obtained is as good as a continuous record for most practical purposes, with the important advantage that the instrument is free from the friction which exists between pen and paper in a pen-recorder. Also, by using a polychrome ribbon or a printing wheel bearing different numbers, distinctive records for a number of circuits can be made on a single chart.

Supply meters which record ampere-hours, watt-hours, etc., on a counting train or otherwise (§§ 113-116) are recording instruments, but this term is generally used to denote graphic recorders.

94. **Power and Power Consumption of Instruments.**—The ratio of torque for full-scale deflection to weight of moving system is a convenient measure of the mechanical power of an instrument. This ratio should be reasonably high in order that the effect of pivot friction may be negligible, but an unduly high torque: weight ratio may be obtained at the cost of high expenditure of electrical energy in the instrument or of cutting down the weight of the movement below the limit of reasonable mechanical strength. The torque of indicating instruments should be not less than 0·05 cm.-grm. per grm. weight of moving system in portable instruments, and not less than 0·15 cm.-grm. per grm. in switchboard instruments. In recording instruments pen friction is much greater than pivot friction and, according to Edgcumbe,* the ratio

Torque for full deflection (cm.-grm.) / (Chart width (cm.) × Pen arm length (cm.))

should be at least 0·05 and preferably 0·1 or higher.

Table 8, based on a more detailed one by Edgcumbe (*loc. cit.*), shows typical values of volt-amperes for full-scale deflection of switchboard indicating instruments. Graphic recording instruments generally consume from 2 to 3 times the power required by the corresponding indicating instruments.

Energy dissipated in the instrument itself may produce error by the heating which it causes (§ 92). Again, the volt-ampere load which may be placed on the secondary of an instrument transformer is strictly limited (§ 108). Not all the power expenditure involved by an instrument may be expended in the indicator itself; for instance, a shunted D.C. ammeter in a 500 A circuit involves, at 0·075 V maximum shunt P.D. (§ 107), a power loss of $500 \times 0 \cdot 075 = 37 \cdot 5$ W, but if 0·05 A goes through the

* *Industrial Electrical Measuring Instruments* (Constable), p. 341.

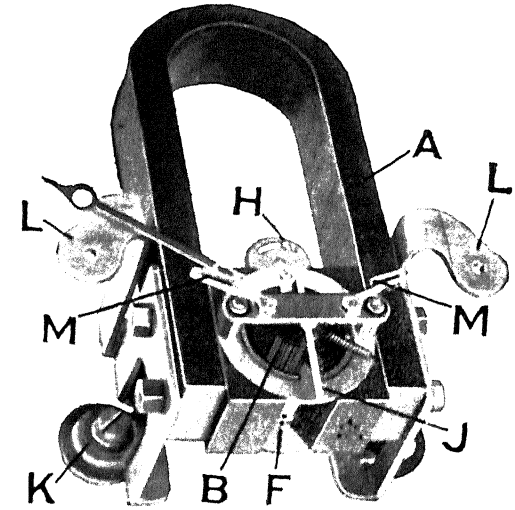
instrument and 499·95 A through the shunt, the power expended in the instrument (including its leads) is

$$0{\cdot}05 \times 0{\cdot}075 = 0{\cdot}003\,75 \text{ W}.$$

TABLE 8.—*Volt-Amperes for Full-Scale Deflection of Indicating Instruments (Switchboard Types).*

Type of Instrument.	Ammeter.	Voltmeter.
Indicating Ammeters and Voltmeters :—		
Moving iron, 6″ or 8″ dial . . .	2 to 4	5 to 10
,, ,, large sector or edgewise .	4 to 8	10 to 20
Moving-coil (permanent magnet) all sizes	Amps. × 0·05 to 0·1	Volts × 0·01 to 0·03
Dynamometer, 6″ or 8″ dial . . .	Amps. × 0·4 to 1·5	Volts × 0·05 to 0·1
Hot wire, 6″ or 8″ dial	Amps. × 0·2 to 0·4	Volts × 0·1 to 0·2
Induction, 6″ or 8″ dial	3 to 7	10 to 20
Indicating Wattmeters :—	Current circuit	Pressure circuit
Induction	2 to 4	5 to 8
Dynamometer	4 to 6	Volts × 0·01 to 0·05

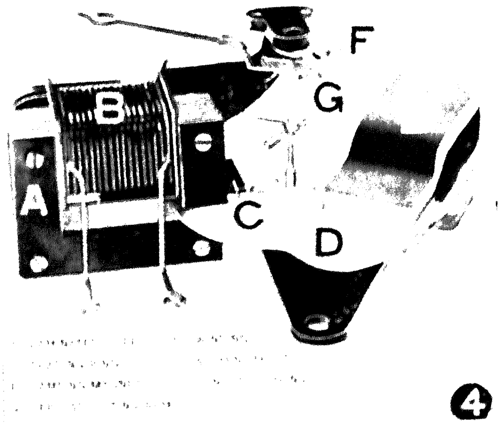
95. Standard Measurements; the Potentiometer. — For ordinary current and pressure measurements of high accuracy, the instrument known as the potentiometer is generally used, in conjunction with standard resistances (§ 20), standard pressure-reducing coils, and standard cells (§ 128). The principle of this instrument is as follows: A wire of very uniform size is divided up into a number of lengths of exactly equal resistance, all in series, of which one length called the slide wire is stretched over a calibrated scale divided into 1 000 parts. A steady current from a secondary battery traverses the whole wire, and this current is adjusted by means of resistance coils until there is a fall of potential of exactly $\frac{1}{10}$ of a volt over the slide wire and each of the other corresponding lengths. This is secured by putting the E.M.F. of a standard cell (§ 128) in opposition to the fall of potential on the slide wire, over a length of the latter nominally equivalent to the pressure of the standard cell, and adjusting the resistance in circuit with the secondary cells until a galvanometer shows that the two opposing pressures are actually balanced. The instrument being thus calibrated ready for use the standard cell is disconnected. Utilising the principle of Ohm's Law, if the current to be measured is made to pass through a known standard resistance (§ 20), the drop in pressure therein



Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF 'SUPERSCALE' MOVING COIL INSTRUMENT.

The moving coil, B, wound on an aluminium frame swings in the magnetic field due to the permanent magnet A. The pivots are internal and work in jewels held in place by the grub screws F. The movement is controlled by a hair spring attached to the zero adjuster J. The evenly divided scale is mounted on the supports L, and the movement of the pointer is limited by stops M. The sensitivity can be varied by means of an adjustable magnetic shunt H, and the whole mechanism is insulated from the case by insulators at K.

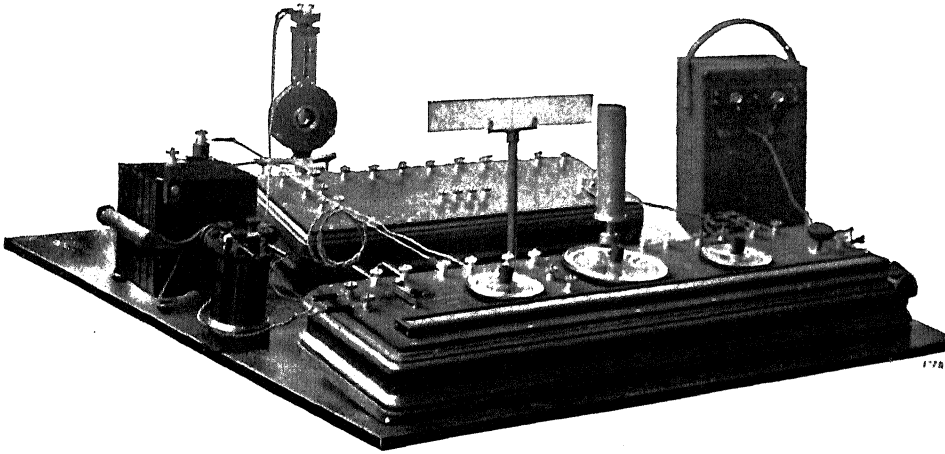


Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF INDUCTION-TYPE AMMETER.

The electromagnet A with laminated core is energised by the current to be measured which passes through the winding B, and half the resulting flux is 'lagged' by a copper ring C. The two fluxes, thus displaced in phase, in passing through the aluminium disc D induce a current in it and consequently a torque which carries the pointer over the scale in opposition to the spiral spring F. The magnet E makes the motion 'dead beat' and the special shape of the disc D causes the scale, which would otherwise be quadratic, to become practically even throughout the working range.

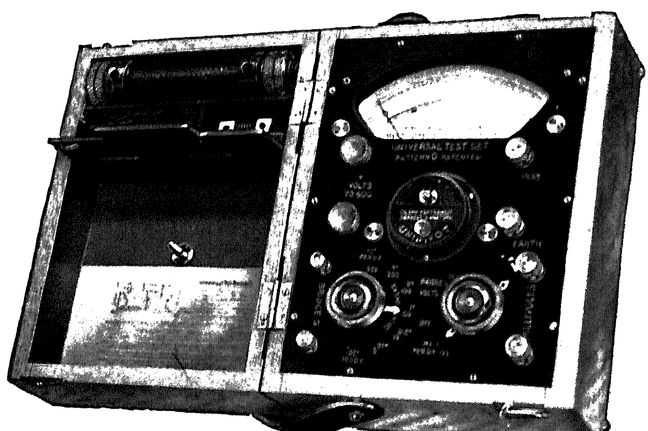
[To face p. 114.



Crompton & Co., Ltd.

Complete Potentiometer Set.

The set comprises a Crompton potentiometer; a reflecting galvanometer, lamp, stand, and scale; standard cells; accumulator cells; a volt box of suitable range for the pressures to be measured; a series of standard resistances for the range of currents to be measured; and a few accessories for special tests. The internal connections of the potentiometer are shown in Fig. 13A.



Cambridge & Paul Instr. Co., Ltd.

Portable Testing Set for D.C. Measurements.

The '**Unipivot**' galvanometer used in this set eliminates troublesome adjustment and accurate levelling. It makes possible the measurement of pressures from 0·000 1 to 600 V; insulation resistances from 20 000 ohms to 1 000 megohms at 500 V; currents from 1 μA to 120 A (or any value with external shunt); and resistances from 10 microhms to 10 ohms, or, with Wheatstone bridge, up to 1 100 000 ohms. The set comprises a micro-ammeter, a universal shunt, series resistance coils, selecting and reversing switches, and standard shunts. Its uses include checking meters; measuring voltage, current, and power; measuring low or high resistances; and locating faults.

[*To face p.* 115.

will be a measure of the current; this drop in pressure is then determined by indirect comparison with the pressure of a standard cell on the slide wire of the instrument. The two pressures are made to oppose each other and exactly balanced, when the galvanometer will show no deflexion. The standard resistances are designed generally so as to give direct readings on the instrument, so that a current of 1, 10, 100, or 1 000 A allows in each case a drop of potential of $\frac{1}{10}$ volt in the standard resistance, this being also the drop of potential in each section of the potentiometer. The actual resistance is a trifle more than is required; auxiliary terminals are then fixed a short way from the main terminals, so that the resistance between them is exactly the required submultiple. The usual values are 0·001 Ω to carry 1 500 A; 0·01 Ω to carry 150 A; 0·1 Ω to carry 15 A; with a drop of 1·5 V

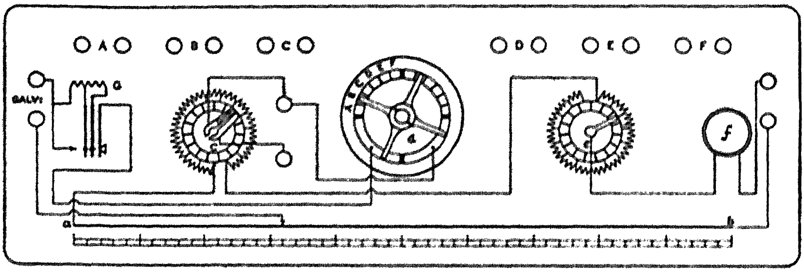


FIG. 13A.—Internal connections of Crompton potentiometer (see also Plate opp.).

over the whole instrument consisting of fourteen equal coils and the slide wire. The larger sizes often consist of water-cooled manganin tubes, as clean tap-water led in by a rubber tube does not affect the resistance.

In Fig. 13A *ab* is the slide wire; *c*, the set of equal potentiometer coils in series with it; *d*, the double pole switch connecting the six pairs of terminals *A*-*F* in succession to the slide contacts; *e*, *f* are the resistance coils and rheostat respectively; and *G* is the galvanometer key. All the moving contacts are under glass and the coils and the scale wire are inside the box. The pair of terminals *A* is assigned permanently to the standard cell in order to prevent confusion in working. Fine fuses are inserted at all the terminals except those for the galvanometer to save the instrument coils in case of accidental connection to high voltage. The two terminals to the right of the potentiometer coil switch, *c*, are used in testing the equality of the series of potentiometer coils. The resistance of the scale wire between 0 and 100 is the same as that of each potentiometer coil, but the scale is extended to 105 so that readings can be taken a little beyond the 100 mark without having to move the potentiometer coil switch.

Many forms of potentiometer are on the market to meet the needs of various classes of commercial testing work. In all these forms as much use as possible is made of direct-reading switch dials and arms. The slide wire itself may be mounted on a marble cylinder and traversed by a rotating contact arm which carries a direct indicating scale. In one form of potentiometer, the slide wire is entirely eliminated by a suitable arrangement of high resistance coils and dial switches. In yet another form a reasonably close 'balance' is obtained in the manner described above, and the deflection on the specially graduated galvanometer scale then indicates what must be added to the switch readings to obtain the unknown P.D. With this deflection-type of potentiometer, direct readings are generally obtainable to 0·001 V; null- or balance-type potentiometers for commercial work generally give direct readings to 0·0001 V (or to 0·000 01 V on reduced range); and special precision instruments permit readings to be taken, by estimation between direct readings, to within 1 microvolt, *i.e.* one-millionth of a volt.

When a pressure is to be determined a definite proportion of that pressure (obtained from a standardised pressure-reducing coil, potential divider, or 'volt box') is similarly compared with the pressure of the standard cell. The volt box consists simply of a large coil of fine wire, wound non-inductively (§ 35 *end*), the terminals of which are connected across the full pressure to be measured. As shown in § 24, there will be an even potential gradient along this wire; and secondary terminals are connected at intermediate points to give exact sub-multiples of the total pressure.* The terminals used in any case are selected so as to

* The principle that the P.D. across any fraction of a volt box is the same fraction of the total P.D. across the latter, holds good only if no current flows through the shunt circuit (§ 107) between the points tapped. For example, the current flowing through a 100 Ω volt box connected across 100 V supply will be 1 A (§ 17) and the P.D. across 1Ω of the box will be 100 V × 1 Ω / 100 Ω = 1 V (§ 24). If this P.D. be measured by an electrostatic instrument (which passes no current, §§ 89, 103) or by a potentiometer (which is adjusted to balance the P.D. between the points of measurement, and then neither adds to nor subtracts from the current in the volt box), it will be found to be 1 V. If, however, 1 Ω of the volt box between two points *AB* be shunted by a measuring instrument of 1 Ω resistance, the effective resistance between *A* and *B* is halved, and the total resistance of the volt-box circuit is reduced to 99½ Ω. The current through the volt box is then 100 / 99½ = 1·005 A and the P.D. between the points *AB* is 1·005 × 0·5 = 0·502 5 V instead of the original 1 V. Thus a volt box provides

give an actual pressure of 1·5 V or less. Thus, for measuring a pressure of 1 000 V, a volt box of 100 000 Ω could be used; then the fall over 100 Ω of this would be one-thousandth of the total, or 1 V only, which would be carried to the potentiometer.

When a resistance is to be measured a current of suitable amperage is passed through it, and the values of this current and the resulting drop of pressure in the resistance are measured as explained; then $R = E / I$. Considerable trouble is often experienced, especially in damp climates, owing to leakage from one circuit to another over the ebonite insulation, which is affected both by light and moisture in the air (§ 74, IV (*d*)); this leakage may be quite appreciable in comparison with the currents in the instrument.

The Drysdale A.C. potentiometer is designed for A.C. measurements, including the magnitude and phase of alternating P.D. The basic principles employed are the same as in the D.C. potentiometer; for a detailed description of the instrument *see Electrician*, Vol. 75, p. 157; Vol. 77, p. 857.

96. **Galvanometers.**—The name galvanometer is applied to a variety of instruments, the purpose of which is to detect weak currents. The relation between deflection and current strength varies with the mechanical and electrical characteristics of the instrument and its circuit, but if the 'law' of the instrument be known quantitative measurements of current, P.D., resistance, etc., can be made.

(i) *Fixed Coil Galvanometers.*—The current to be measured is passed through a fixed coil the field of which deflects a permanent magnet against the torsion of a suspending fibre or against the control exerted by the earth's magnetic field. If the magnet be attached to the back of a small mirror its deflection is greatly magnified by the movement over a distant scale of a spot of light reflected by the mirror.

In the *tangent galvanometer* a horizontal magnetic needle carried by a vertical pivot is placed at the centre of a circular coil the plane of which is vertical and coincident with the direction of the earth's field. When current passes round the coil the needle is deflected through an angle θ and the current in amperes = $K \tan \theta$, where K is the 'constant' of the galvanometer. If the

uniform potential gradient only so long as no current is shunted from (or added to) part of the volt box. *See also* § 107 (*c*).

coil be turned about a vertical axis in the same direction as the deflection of the needle it will overtake the latter, and if the angle through which *the coil* has been turned is α, when its plane is again coincident with the needle, the value of the current is $K^1 . \sin \alpha$, K^1 being a different 'constant.'

The *linesman's detector,* used principally for indicating current when identifying or testing the continuity of circuits (Chapter 40), has a pivoted magnetic needle which is deflected when current flows through an adjacent fixed coil. Two windings are generally provided, one of many turns of fine wire and about 100 Ω resistance for currents of a few milliamperes, and one of a few turns of thick wire (about 0·2 Ω) for heavy currents—up to 150 A if the coil be shunted (§ 107). This instrument may be used for rough comparisons of currents, but a testing set (§ 106) should preferably be used.

(ii) *Moving-Coil Galvanometers.*—The D'Arsonval galvanometer is the prototype of moving coil, permanent magnet voltmeters, and ammeters (§ 101) from which it differs only in having a fibre suspension instead of pivots for the moving coil and a reflecting mirror instead of a pointer to magnify the deflection. By eliminating the soft iron core inside the moving coil, replacing the latter by a single conductor of silvered glass or quartz, and reducing to a minimum the length of air gap, we arrive at the *Einthoven string galvanometer.* When current passes through the 'string' the latter is deflected (§ 33); the deflection is magnified by a microscope and recorded photographically. A small fraction of one-millionth of an ampere can be measured. Replacing the magnetic poles by plate electrodes at known potential and the current carrying fibre by a fibre connected to a source of potential under investigation, the instrument becomes the *string electrometer.*

An ordinary moving-coil galvanometer is essentially a D.C instrument (§ 89, *a*), but if provision be made to vary the tension of the suspension, the natural frequency of the moving system can be made to coincide with the frequency of alternating current used in A.C. bridge measurements (§ 120), etc. Thus arranged the instrument is a *vibration galvanometer.* Its coil vibrates in resonance (§ 47) when traversed by A.C. of the frequency for which it is adjusted, and when the band of light, so produced on its scale, is reduced to a steady spot it is known that no current i

flowing through the instrument, *i.e.* balance has been obtained in the case of a bridge measurement.

(iii) *Ballistic Galvanometers.*—Either a moving needle or a moving-coil galvanometer may be used ballistically if its damping (§ 90) be small, and its time of vibration not less than, say, 10 secs. The principle used is that when the whole of a transitory current flows through the galvanometer before the moving system has time to move appreciably, the subsequent deflection depends upon the *quantity* (§ 28) of current which has passed. The instrument must be calibrated experimentally and its principal use is in determining magnetic flux or flux density by measuring the quantity of electricity induced in a 'search coil' when the latter is rotated in or withdrawn from the field in question (§§ 36, 121).

97. **Commercial Measurements.**—For the ordinary measurements of commercial electric supply an accuracy of 1 or 2 °/。 is generally quite sufficient (§ 92), and self-contained instruments are employed.

For the measurement of current and pressure 'ammeters' and 'voltmeters' are used respectively (§ 98). These may be either plain, indicating-dial instruments, showing the reading at any particular instant, or recorders, marking the current or pressure continuously on a revolving chart, divided up into hours (§ 93).

For measuring low or medium resistance the 'Wheatstone bridge' (§ 120) in one form or another is ordinarily used, while for very high resistances (especially insulation resistances) ohmmeters calibrated to read direct in megohms are employed, each instrument having its own magneto-generator for supplying the testing current (§ 119).

For measuring ampere-hours integrating 'ampere-hour meters' are used, having a clock mechanism and a train of dial wheels, in conjunction with current-measuring coils (§ 114). Electrolytic meters are also used for this purpose (§§ 28, 114).

'Watt-meters' (§ 109) contain a pressure-measuring coil and a current-measuring coil, so arranged with regard to one another that the indicating needle shows the product in watts. They may either indicate the power at the moment or record it continuously on a chart marked out in hours.

Watt-hour meters (§ 115) integrate the total work and record the result on a series of dials. Usually they are calibrated directly in Board of Trade units (kWh). The term 'meter,' as ordinarily used, includes this class of meter, as used to measure the value of the electric supply to buildings (§ 270)—corresponding, except for its greater accuracy, to the gas meter—as well as ampere-hour meters (§ 114).

Other instruments used for commercial measurements are dealt with in §§ 111-123 inclusive. (*See also* index.)

98. **Ammeters and Voltmeters.**—Since the current flowing through a non-inductive resistance is proportional to the P.D.

across the latter (§ 17) it follows that any current-measuring instrument can also be used to measure voltage. The only distinction between the two cases is that a voltage-measuring instrument for connection between two poles or phases of supply must be of high resistance to limit the current flowing and so restrict the expenditure of power within the instrument (§ 94), whilst any instrument used to measure the current flow in supply conductors must be of low resistance in order to reduce the I^2R losses (§ 49) in the instrument if the latter is connected in series with the main circuit or in order that it may be operated by a low-P.D., low-loss shunt (§ 107*a*). The high resistance of the voltmeter may be secured by connecting a suitable resistance in series with it, the instrument proper being identical with an ammeter except as regards the marking of the scale. By varying the resistance in series with the instrument, the range may be altered (§ 107*d*).

Thus, theoretically, any ammeter can be used as a voltmeter and *vice versa*. In practice, the matter is not quite so simple. For permanent installations the instrument must be calibrated to read directly in amperes or volts, as the case may be, and might as well embody any modifications in construction which render it more suitable for the purpose it is to serve. Electrostatic instruments are not convenient or economical for current measurements (§ 89 iv). Hot wire instruments are generally shunted when used for current measurements (§ 99), and a shunted ammeter can be designed for the same small operating current which is alone economically permissible in a circuit connected across the mains. In other words, a shunted hot-wire ammeter may be identical with a hot-wire voltmeter, but when used for voltage measurement it must be connected in series with a suitable resistance (*see* Ex. § 107*d*). For the same reasons, a shunted moving-coil permanent magnet ammeter can be used as a voltmeter without change of winding (*see* Ex., *loc. cit.*; also § 106). Conditions are different where moving iron instruments are concerned. In ammeters of this type the main current (up to 500 or 600 A) is generally passed through the instrument winding which is therefore a few turns of thick wire providing, say, 500 ampere-turns (§ 42). An equal number of ampere-turns is needed to operate a moving-iron voltmeter, but the current being small (to keep the power consumption low), the number of turns must be high. By

using many turns of fine wire the requisite ampere-turns are obtained, but if the instrument is to be used in A.C. circuits, non-inductive resistance must still be connected in series with the instrument in order that the net inductance of the circuit may be low (§§ 44, 100). Thus, for practical reasons, there are considerable differences between the constructions of moving-iron ammeters and voltmeters. In a moving-coil ammeter or voltmeter there need be only 0·3 to 1 ampere-turn which can be provided by the same winding and an equally small current in both cases.

In A.C. circuits it is generally the R.M.S. value of current or voltage which is to be measured (§ 29), hence not every type of instrument can be used (§ 89). For special purposes crest voltage (§§ 30, 105) must be measured, or the complete wave of current, or voltage must be traced (§ 118). An ammeter should be used in every important circuit; the current consumption alone is sufficient general indication of power consumption if the voltage be constant (as it generally is), and in A.C. circuits, if the power factor be reasonably constant (*see also* §§ 110, 114). The use of shunts and instrument transformers is discussed in §§ 107, 108.

99. Hot-wire Ammeters and Voltmeters.—The expansion of a fine wire due to heat developed by the current to be measured (§§ 89 ii, 98) is used to move an indicating pointer. Instead of measuring the actual expansion, the sag of the hot-wire (which is much greater than the expansion which causes it) is magnified by the yet greater sag in a tie wire between a fixed point and the centre of the hot wire. The latter is necessarily very fine and is easily burnt out; the principal use of the instrument is in the test room. Hot-wire instruments are unaffected by stray fields and can be used for either D.C. or A.C. of any frequency or wave form. The zero is liable to 'creep'; temperature errors may be serious; and the P.D. across the instrument or its shunt must be at least 0·2 V, *i.e.* the power loss in a hot-wire ammeter is about three times that in a moving-coil instrument (Table 8, § 94).

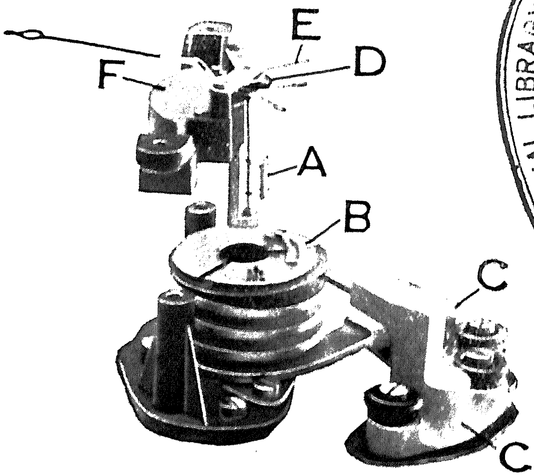
The *Duddell thermo-ammeter* is a combined thermal and electromagnetic instrument especially suitable for measuring currents from a few amperes down to a few milliamperes at high frequencies. The current to be measured is passed through a heating element of wire or platinised mica which is mounted below

a bismuth-antimony thermo-couple (§ 122) connected in the circuit of a low resistance moving coil, permanent magnet instrument (§ 101). This instrument combines independence of wave form and frequency with the high sensitivity obtainable by using a powerful permanent magnet, whilst avoiding the mechanical difficulties of the ordinary hot-wire instrument (*see also* § 118).

100. Moving Iron Ammeters and Voltmeters.—The differences between ammeters and voltmeters of this type are noted in § 98. The general principle of both instruments is the same. A suitably shaped piece of soft iron is drawn into a coil through which is passed the current to be measured; or the iron may be moved from a weaker to a stronger part of the field so produced; or the moving iron may be repelled from a stationary piece of iron magnetised by the same field. In any case the moving iron is attached to the spindle carrying the pointer, and its movement takes place against the control of a spring or gravity (§ 90). According to the shape and disposition of the iron, the variation of deflection with current may be altered within wide limits.* So long as the iron is unsaturated the flux produced in it varies with the current in the magnetising coil (§§ 42, 81), hence the deflecting force on the iron (varying with flux × current) is proportional to the square of the current. The instrument is therefore inherently suitable for A.C. measurements (§ 89 *b*). Due to hysteresis in the iron (§§ 34, 81) there is a tendency for the instrument to read high on descending values. Again, the winding of a voltmeter of this type is necessarily inductive (§ 98), and unless the inductance can be "swamped" by plenty of non-inductive resistance (§ 44) the impedance of the instrument circuit, and therefore the calibration of the instrument, varies with frequency. It is claimed for the latest moving iron instruments that the error is less than 1 °/₀ whether D.C. or A.C. of 50 or 100 cycles per sec. be used. In the absence of suitable guarantees, moving-iron instruments should be calibrated with A.C. of the frequency and wave form on which they are to be used.

The Dransfield 3-phase voltmeter is a moving-iron instrument with two coils. The latter have one common terminal and the other ends of the coils are connected through inductance and

* If the scale be logarithmic (like that of a slide rule) overloads of 100 °/₀ or so can be read with sufficient accuracy whilst retaining an open scale within the normal range.



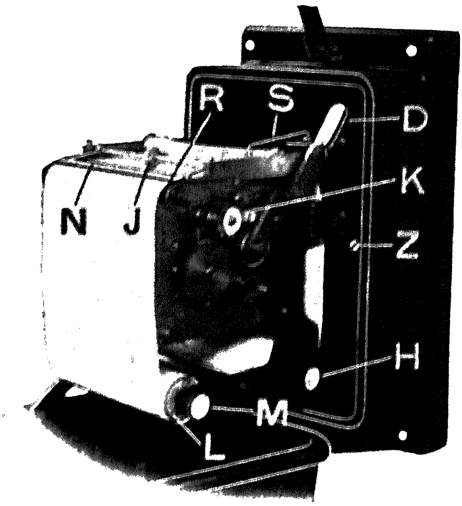
Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF 'SUPERSCALE' MOVING IRON AMMETER FOR 100 A
(Moving element withdrawn from coil for clearness.)

The current flows from the terminals C round the copper winding and thus magnetises a fixed piece of iron attached to the regulating lever B. This piece of iron repels another small iron A attached to the pointer spindle, and the movement of the latter is opposed by the spiral spring D, attached to the zero adjusting lever E. The motion is rendered 'dead-beat' by a pneumatic damper F. Owing to the quality and shape of the iron used, the hysteresis is negligible and the indications with A.C. and D.C. are practically identical.

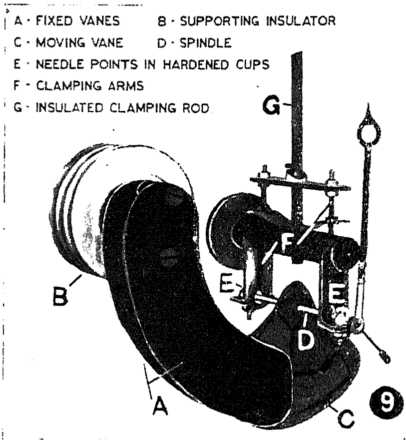
WORKING PARTS OF THE 'INK-WELL' GRAPHIC RECORDER.

The inking member consists of a capillary tube S, which carries the ink from a fixed central reservoir on to the chart N. The clock K draws the chart at a constant speed of, say 1 in. per hour, by means of the toothed wheel J from the spool H on to the roller L. D is the clock winding lever and Z the zero adjustor. In this instrument the supply of ink is unlimited and the friction between pen and paper is negligible.



Everett, Edgcumbe & Co., Ltd.

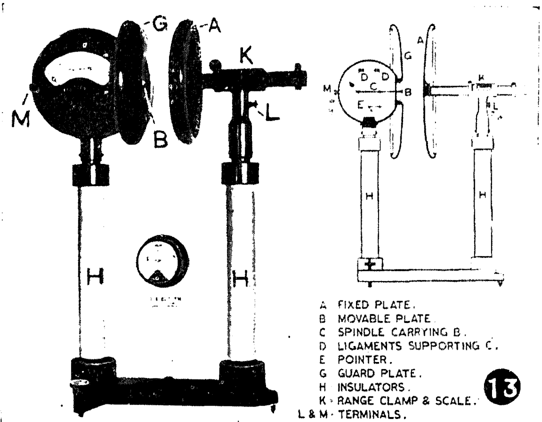
To face p. 1[illegible]



Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF H.T. ELECTROSTATIC VOLTMETER.

The moving vane C is attracted by the fixed vane A, the motion being opposed by a spiral spring. The movement is rendered 'dead-beat' by a pneumatic damper, which has been removed for the sake of clearness. The spindle D has needle points in hardened cups at E. The insulated clamping rod G works in conjunction with the clamping arms F, and the whole is carried by the insulator B. These voltmeters are used direct up to 7 000 V and through series condensers for higher voltages.



Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF E.H.T. ELECTROSTATIC VOLTMETER (ABRAHAM TYPE).

A movable plate B, within a guard-plate G, is attracted by the fixed plate A, and so carries the pointer over the scale, the movement being damped by a pneumatic device. The spindle C is supported by ligaments D. The instrument is mounted on insulators H; the terminals are at L and M; and K is a range clamp and scale. These instruments are constructed for all pressures up to 300 000 V, and, owing to the absence of any solid or liquid dielectric (*e.g.* oil), the readings are independent both of frequency and of wave form. All projections are carefully rounded off so as to avoid 'brushing.'

[*To face p.* 123.

resistance respectively to the second and third terminals of the instrument. The instrument serves the double function of (*a*) measuring the voltage of a 3-phase system, and (*b*) indicating incorrect connections or phase rotation, or failure of h.t. or l.t. fuses in the circuits of the 3-phase instrument transformer (or two single-phase transformers) which serves the voltmeter itself and also P.F. indicators, watt-meters, etc. Normally the instrument indicates the 3-phase voltage, but its scale is marked with lettered lines to one or other of which the pointer falls back in event of wrong connections or blown h.t. or l.t. fuse in the instrument transformer circuit.

101. **Moving-coil Ammeters and Voltmeters.**—There are two main types of instruments to be considered under this heading, *viz.* :—

(*a*) Moving-coil, permanent magnet instruments; and
(*b*) Moving-coil, dynamometer type instruments.

The two types have many points of similarity but also important differences (*see also* §§ 89 iii, 94).

(*a*) *Moving-coil, Permanent Magnet Instruments*, commonly called 'moving-coil instruments,' for brevity, consist essentially of a fine wire coil so pivoted that it can swing in the intense magnetic field produced in a narrow air gap between a permanent magnet and a soft iron core. The latter is commonly cylindrical, and coaxial with the spindle of the moving coil which has a small clearance between the core inside it and the cylindrically-bored pole shoes of the magnet outside it. The permanent magnet and core are stationary, and the moving-coil is deflected against the control of spiral springs which serve to carry current into the coil. The deflecting force is produced by the current-carrying conductors of the coil and the magnetic field in the air gap (§ 35, footnote). The field in the narrow annular gap is radial and practically uniform, hence the deflecting force is nearly proportional to the current. This being so, and the controlling force exerted by the springs being nearly proportional to the deflection, it follows that the scale is practically uniform in this type of instrument. In the Record 'Cirscale' instruments the same principle is employed, but the construction is modified to increase the scale length. A C-shaped magnet is used, and one pole is provided with two circular-plate extensions between which projects a single similar plate attached

to the other pole. There are thus obtained two narrow air gaps between the circular plates, and the moving-coil is pivoted on the line of centres of the interleaved pole plates. The central plate is 'necked' so that the moving-coil can turn through 300° or even 330°.

The moving-coil can accommodate a considerable number of turns of fine wire and the field is very strong, hence the instrument is highly sensitive and the power consumption is low (§ 94). For currents exceeding $\frac{1}{4}$ A or so, ammeters of this type must be shunted (§§ 98, 107). Damping is provided by eddy currents induced in the aluminium 'former' on which the coil is wound. The direction of the deflecting force reverses with the direction of the current, hence these instruments are suitable only for D.C. measurements (see, however, vibration galvanometers § 96, ii). The intensity of field in the narrow air gap is such that stray fields (§ 92, ii) are of negligible effect. When the instrument is used as a voltmeter the influence of temperature can be eliminated by making the series resistance (§ 98) of manganin or other wire with zero temperature coefficient. In the case of the ammeter no appreciable 'swamping' resistance can be used (the shunt P.D. being limited to 75 mV, § 107*a*), and it is inadvisable to use a copper shunt because the temperatures of shunt and moving-coil may differ considerably. (*See also* § 118.)

(*b*) *Moving-coil, dynamometer-type instruments*, generally called 'dynamometer instruments,' differ from the permanent magnet type in that the stationary field is produced by a pair of coils embracing and connected in series with the moving-coil. The field is no longer constant but varies with the current (or voltage) measured, hence the deflecting force varies with the square of the current and the instrument is equally suitable for D.C. or A.C. measurements, provided that there are no constructional parts in which eddy currents (§ 39) can be induced. The coils have no iron cores, hence the field is relatively weak (§§ 42, 43), and large coils must be used to obtain adequate working forces.* Because the working fields are weak, stray fields introduce serious errors unless the instrument is built astatically (§ 92, ii). The scale is not uniform but, like all square-law scales, crowded at its lower end.

* This objection is overcome, but at the cost of other difficulties and complications, by iron-cored dynamometer-type ammeters, voltmeters, and watt-meters (§ 109).

In ammeters of this type the main current can generally be taken through the fixed coils, but 5 A is about the maximum for the moving-coil which is therefore generally shunted. If the whole instrument be shunted the field of the fixed coils is reduced unnecessarily. In voltmeters the same current flows through both windings. Because of the many turns required to obtain suitable field strength the pressure drop in dynamometer ammeters is high (§ 94). Ammeters and voltmeters of this type are rarely used outside laboratories.

The *Kelvin ampere balance,* used for current measurements in standardisation tests, has a balance beam carrying a coil at each end. These coils lie between pairs of fixed coils and all the coils are electrically in series. The connections are such that both sets of coils tend to tilt the beam in the same direction and balance is restored by adjusting weights. The deflecting force which is thus 'weighed' is proportional to the square of the current through the coils.

102. Induction Ammeters and Voltmeters.—These instruments operate on the principle of the induction motor (Chapter 28). The induction-type supply meter (§ 115) is actually a miniature induction motor which rotates continuously whilst energy is supplied through it. In the ammeter and voltmeter, however, the rotation is limited by a control spring, and the torque produces a deflection which is proportional to the square of the current or voltage measured.

In one form of these instruments there are two field circuits connected in parallel. One branch is highly inductive and the other is mainly non-inductive resistance. The net result is to produce a rotating field which induces current in and exerts a drag on a copper or aluminium disc mounted on the same spindle as the pointer. In another form a single winding excites an electromagnet, part of the pole face of which is covered by a copper sheath. The alternating flux induces eddy currents (§ 39) in both the copper sheath and the copper or aluminium disc on the spindle, and the interaction between these eddy currents produces the deflecting torque.

It will be understood that these instruments are applicable only to A.C. measurements. In service they are rugged and simple (though their complete theory is complex), and they can easily be provided with long scales (say 330°). They are admirable

for switchboard service, but not for general testing work because the torque varies with frequency and wave form. In voltmeters the effect of frequency is less marked than in ammeters because the change in impedance (§ 44) of the inductive circuit of the former compensates to some extent for the change in torque. Error due to stray fields is not likely to be serious, but the temperature error (§ 92 i) is considerable due to change in resistance of the parts in which the eddy currents are induced.

103. Electrostatic Voltmeters.—The force of electrostatic attraction between plates or vanes at different potential is proportional to the square of the P.D. between them, but is so small that, for low and medium voltages, the mechanical construction of an electrostatic voltmeter must be so delicate that the instrument is not suitable for commercial service. With higher voltages, however, the operating forces become so great that a relatively robust construction can be employed. Also, at such voltages, the insulation problem is simpler in electrostatic voltmeters than in other types. For low-voltage measurements a number of vanes are mounted one below the other on a common spindle and attracted by an equal number of pairs of fixed plates or 'cells.' The P.D. to be measured is connected between the vanes and the fixed cells. Since the deflecting force varies with the square of the voltage the instrument is equally applicable to D.C. and A.C. circuits (§ 89 *b*). The indications are independent of temperature, frequency, wave form, and stray magnetic fields, but error is introduced by stray electrostatic fields, unless the instrument is suitably screened.

For high-voltage measurements (from 10 000 to 200 000 V) the attraction between two parallel plates is sufficient to operate the indicating mechanism. One plate consists of a large stationary disc, the other of a smaller disc surrounded by a 'guard ring' which is of the same outside diameter as the fixed disc; the object of this arrangement is to secure a uniform field between the fixed and moving discs. The range of measurement may be increased by increasing the distance between the discs. (*See also* § 107 *c*.) If the plates be submerged in oil the range and sensitivity are increased, because the operating force increases with the specific inductive capacity (§ 46) of the dielectric, and the dielectric strength of oil is greater than that of air, hence higher voltages may be used or, alternatively, a smaller gap

(giving greater sensitivity) may be used for a given voltage. For laboratory measurements up to 250 000 V compressed nitrogen (§ 78) at a pressure of 10-12 atmospheres has been used as dielectric in electrostatic instruments. In all cases a high resistance should be connected in series with the instrument to limit the current flow in event of flash-over; otherwise the instrument may be destroyed before the protective fuses melt. Series resistance has no effect on the indication of an electrostatic voltmeter, because there is no appreciable current flow (§ 89 iv). The fact that no current flows through these instruments is of economic importance where high voltages are concerned, because even 10 mA corresponds to 1 kW at 100 000 V (unity P.F.).

See also current measurement by electrostatic voltmeter (§ 89 iv); charge indicators (§ 104); leakage indicators (Chapter 40); and electrostatic oscillographs (§ 118).

104. Electrostatic Charge Indicators.—These are essentially electrostatic voltmeters (§ 103) without pointer or scale. The moving vane has a red spot or line which is normally hidden, but which shows behind a sighting aperture when the indicator is applied to a 'live' conductor. A calibrated electrostatic voltmeter could be used for the purpose (with the advantage of actually measuring the P.D. between conductors or between conductor and earth), but simple uncalibrated devices can be made strong, cheap, and easily portable. For use in detecting live wires, want of continuity, leakage, etc., in D.C. or A.C. systems at from 80 to 700 V between conductors or to earth, there is on the market a device about the size and shape of a lead pencil. A metal point and casing at opposite ends of the device are connected respectively (in series with a high internal resistance) to a fixed electrode and an adjacent flexible vane; the latter is attracted and shows a warning signal when there is a P.D. between the terminals. For high-voltage circuits a testing point connected to a combination of fixed and moving vanes (mounted on an insulating handle) is brought into contact with the conductor to be tested; if the latter be live the vanes are charged similarly and the moving vane is repelled. Another device depends upon the attraction of a balanced vane by a live high-voltage conductor; this device can be used without making electrical contact with the conductor. Yet another detector, depending on a different principle (static sparking) is described in *El. Rev.*, Vol. 90, p. 752.

105. Spark Gap Voltmeters.—There is a definite relation between any voltage and the length of spark gap which it will break-down. Hence, if a long gap be reduced until the first spark passes the value of the voltage can be read from a calibration table (§ 78) or curve, or a pointer moving with the adjustable electrode may indicate the voltage on a graduated scale. The break-down depends upon the *maximum* value of the voltage (§§ 30, 72)—hence the name 'crest voltmeters'—but if the wave form be sinusoidal or of other known form the instrument can be calibrated in R.M.S. values. For insulation tests (§ 30) and in X-ray work, however, it is the peak value of the voltage wave which is to be measured. The use of spark gap voltmeters is limited to high pressures (say over 10 kV); D.C. or A.C. pressures can be measured, but the calibration is different in the two cases.

Air is generally used as dielectric between the electrodes because it is self-repairing and is of lower dielectric strength than oil (*i.e.* greater sensitivity is obtained, the gap for given P.D. being greater). Ionisation of air, produced by sparking or by an electric arc, reduces the dielectric strength, hence a spark gap voltmeter must not be used near an arc lamp, and the gap length across which the *first* spark passes must be taken as determining the voltage. Up to 30 000 V needle electrodes should be used (these given greater gap lengths for given voltage), but for higher pressure spherical electrodes give results which are less affected by frequency, wave form, and atmospheric conditions. The diameter of the spheres must be large enough to prevent corona or brush discharge preceding the spark, otherwise the air is ionised and the relation between gap length and voltage becomes quite erratic. A table of R.M.S. voltages from 10 to 400 kV and corresponding gap lengths between spheres from 62·5 mm. to 500 mm. diameter is given, together with particulars of corrections required, in B.E.S.A. Report No. 137.

Crest voltages can be determined, often more conveniently and generally with at least equal accuracy, by an oscillograph or by the point-by-point method (§ 118).

106. Testing Sets.—There are a number of useful portable testing sets on the market which are both accurate and handy. They may be used either for checking other instruments or for making measurements where no others are provided. Typical

sets have two moving-coil millivoltmeters (§ 101), generally reading from zero to 150, the scale reading being multiplied by one or other of several factors according to the range employed. This type of instrument is suitable only for D.C. measurements. A single moving-coil instrument can be used for both pressure and current measurements (§ 98), but it is more convenient to have two instruments as this simplifies connections and makes possible simultaneous readings of pressure and current, and thus calculation of D.C. power (§§ 50, 54).

For volt measurements the case contains a subdivided resistance coil (§ 95), of about 60 000 Ω resistance, which can be connected across the pressure to be measured. There is a positive terminal V + attached to one end of the coil, and negative terminals V −, for 1·5, 15, 150, and 600 V, respectively, attached to suitable points on the resistance coil, so that the pressure can be read off directly.

For current measurements, standard resistances (§§ 20, 95) are connected in series into the circuit (*not* across it) and the drop in pressure across the resistance is actually measured, as explained in § 95; the usual ranges are 1·5, 15, 150, and 600 A, and the instrument reads directly in amperes in the three lower ranges. The flexible connecting leads supplied with these instruments, or others of exactly the same resistance, must be used for current measurements; otherwise the readings will be incorrect.

Resistance measurements can sometimes be made conveniently by noting corresponding values of P.D. and current (§ 119); in other cases the testing set includes a wheatstone bridge (§ 120).

Similar testing sets with hot wire or electrostatic instruments could be used for D.C. or A.C. measurements, but these instruments are not suitable for portable service (§§ 99, 103). Methods of measuring A.C. power are described in §§ 109, 110.

107. Extending the Range of Instruments: Shunts and Potential Dividers.—The current which can safely be passed through an ammeter of other than the moving iron type (§ 100) is generally limited to a few amperes and sometimes to a fraction of 1 A. Much heavier currents (up to, say, 20 000 A) can be measured by passing through the instrument a definite fraction of the total current; this fraction is obtained by a shunt, or, in the case of A.C., by a current transformer (§ 108). The scale is calibrated in main-current values, unless the instrument is to be

used with different shunts in which case the indication must always be multiplied by the appropriate factor.

Similarly, the range of a voltmeter can be extended almost indefinitely by applying to the instrument a definite fraction of the total P.D. (obtained by a volt box, § 95, or a potential transformer, § 108), or by connecting a suitable resistance in series with the instrument. Condensers can be used with electrostatic instruments as explained below.

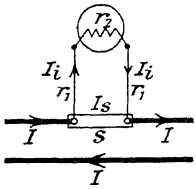


FIG. 14.—Shunted ammeter.

(*a*) *Shunts.*—Referring to Fig. 14, if an ammeter of resistance r_2 Ω be connected, by two leads each of resistance r_1 Ω, to the terminals of a 'shunt' of resistance s Ω, the pressure drop in the instrument circuit equals that in the shunt. Denoting the total resistance of the instrument circuit by $R = 2r_1 + r_2$, we have: Pressure drop in instrument circuit $= I_iR$ (§ 24) $= I_ss$ (the pressure drop in the shunt). Therefore $I = I_iR / s$. The 'multiplying power' of the shunt (= main current / instrument current) $= I / I_i = (I_i + I_s) / I_i = \left(I_i + \frac{I_iR}{s}\right) / I_i = I + \frac{R}{s} =$ say, n. Hence, if the multiplying power is to be n (generally 10 or a decimal multiple thereof): $\frac{R}{s} = n - 1$ and $s = \frac{R}{(n-1)}$, *i.e.* the resistance of the shunt must be $\frac{1}{(n-1)}$ times the resistance of the instrument (including its leads).

In order that the multiplying power of the shunt may not vary R and s must be constant or they must vary always in the same ratio. If both branches consisted only of copper, the ratio R / s would be constant if the temperature of shunt and instrument were always the same; this cannot be guaranteed, hence it is usual to make the shunt of manganin and to 'swamp' the copper in the instrument circuit by using as much manganin as possible in this branch (§§ 92 i, 98).

The actual resistance, s, of the shunt should be low in order that the energy dissipated in it (I^2s watts, § 49) may be low. The pressure drop, I_ss, must, however, be sufficient to operate the instrument satisfactorily, and British Standard values for this drop (at rated current) are : 0·075 V for first- and second-grade

indicating instruments (§ 92); 0·2 V for recording instruments; and either 0·000 5 or 0·001 V per scale division for indicating sub-standard instruments, of the moving-coil, permanent magnet type (§ 101 *a*) in each case. For instruments of other types the P.D. across the shunt at rated current may not exceed 1 V. The total resistance of the leads in series with the instrument across the shunt should not exceed 0·05 Ω for portable instruments and 0·025 Ω for switchboard instruments at 20° C. The material and construction of the shunt and instrument leads should be such that alteration in instrument indication, due to thermo-electric E.M.F. (§§ 122 *b*, 129) does not exceed 0·25 %. The temperature rise of a shunt when carrying rated current for 2 hrs. should not exceed 80° C. Best ventilation for laminated shunts is generally obtained by mounting with the terminals in line horizontally and the plane of the plates vertical. (*See also* B.E.S.A. Reports 89 and 90; and 'Multiple-Unit Shunts for the Measurement of Very Heavy Currents,' by M. B. Field, *Jour. I.E.E.*, Vol. 58, p. 661.)

(*b*) *Magnetic Shunts* are used in some supply meters and in some moving-coil indicating instruments as a means of adjusting the active magnetic field and so providing for fine adjustment of the 'law' of the instrument. A piece of soft iron of relatively small section bridges the main air gap more or less completely, and thus provides a shunt path for some of the magnetic flux.

(*c*) *Potential Dividers.*—(i) *Volt Box.*—The principle of the 'volt box' has already been explained in § 95. As there noted, the uniform potential gradient in a uniform, non-inductive resistance connected across the voltage to be measured, is not disturbed if an electrostatic instrument be connected across part of the resistance; neither is the gradient disturbed appreciably if an instrument be used which is of very high resistance, compared with the section of the volt box across which it is connected. In any case the total resistance of the volt box must be high otherwise the power consumption therein becomes excessive. This method of extending the range of a voltmeter is applicable to both D.C. and A.C. instruments, but in practice series resistance (see (*d*) below) is generally used for D.C. voltmeters and potential transformers (§ 108) for A.C. instruments.

(ii) *Condensers.*—The range of an electrostatic voltmeter (§ 103) can be extended by connecting a condenser in series with

the instrument. The P.D. applied to two condensers connected in series is divided between these in *inverse* proportion to the capacities of the condensers; hence if the P.D. across an electrostatic instrument is to be made a small fraction of the total P.D. the instrument must be connected in series with a condenser the capacity of which is much smaller than that of the electrostatic instrument. This is a matter of practical difficulty, because the capacity of the instrument is very small and changes with the position of the vanes. An alternative method is to connect several relatively large condensers in series across the mains and to connect the electrostatic instrument in parallel with one of these. This arrangement is the electrostatic equivalent of the volt box and the small capacity of the instrument does not affect appreciably the potential gradient in the chain of condensers across part of which it is connected. Even the smallest leakage currents make the readings vary with frequency.

(*d*) *Series Resistance*.—As explained in § 98, any ammeter can—subject to certain practical considerations—be used as a voltmeter by connecting a suitable resistance in series with it. The range of the instrument can be increased by increasing the series resistance.

Example.—Suppose that, in Fig. 14, $r_1 = 0{\cdot}025\ \Omega$ and $r_2 = 1{\cdot}5\ \Omega$, and that the instrument gives full scale deflection when the shunt P.D. $= 0{\cdot}075$ V. Then: Current through instrument for full scale deflection $= 0{\cdot}075 / (2 \times {\cdot}025 + 1{\cdot}5) = 0{\cdot}075 / 1{\cdot}55 = 0{\cdot}0485$ A. If this instrument is to be used as a voltmeter measuring up to v volts it must be connected in series with a resistance R such that $v / (R + 1{\cdot}5) = 0{\cdot}0485$. If $v = 220$ V, we have: $220 / (R + 1{\cdot}5) = 0{\cdot}0485$; whence $R = 4\,534{\cdot}6\ \Omega$.

An ammeter of resistance $r\ \Omega$ reading i amperes per scale division will read 1V per scale division when connected in series with a resistance $R = (1 - ir) / i\ \Omega$.

Hot wire, moving iron, and moving-coil voltmeters (§§ 99-101) are operated by a current which is proportional to the voltage to be measured. The full scale deflection corresponds to a particular value of this current, and in order to extend the voltage range it is only necessary to connect in series with the instrument such a non-inductive resistance that the higher voltage sends the full-scale current through the combined resistance of the instrument and series resistance. The range of the voltmeter is multiplied by n if the instrument be used in series with a resistance $= (n - 1)$ times its own resistance.

Electrostatic voltmeters, however, depend upon the potential of the vanes (§ 103), and this is unaffected by series resistance,* hence the range of these instruments *cannot* be increased by series resistance (*see*, however, § *c* (ii) above).

108. Instrument (Potential and Current) Transformers.— Instrument transformers are used with A.C. indicating, recording, and integrating measuring instruments and with relays and automatic devices of various descriptions when the main current is too heavy and/or the main pressure too high to allow direct connection between the instrument, etc., and the main circuit. They are applicable only to A.C. circuits. The transformer windings are electrically distinct (auto-transformers (Chap. 17) may *not* be used), the primary being connected with the main circuit and the secondary with the instrument, etc. Instruments used with current or potential transformers should be calibrated with them, the scale being marked to show the main circuit values of current, voltage, power, etc. The use of these transformers permits instruments to be lighter in mechanical construction and electrical insulation than would otherwise be possible; accuracy and safety are enhanced, and a standard type of instrument can be used for measurements over a very wide range. About 600 A and 750 V are the extreme limits for direct-connected ammeters and voltmeters (excepting electrostatic instruments, § 103). By the use of instrument transformers high voltage is excluded from the instrument circuits,† and the main current (and its field and eddy currents induced thereby) is kept away from the instrument. For example, a low-pressure wattmeter can be used with current and potential transformers to measure power in a high-voltage circuit.

In current transformers a low-resistance primary winding of one or a few turns is connected in series with the main circuit,

* There being no current flow, there is no pressure drop in the series resistance.

† If the main circuit is at high potential, the insulation problem is transferred from the instrument to the instrument transformer where it is more easily dealt with but still remains of vital importance. By earthing the secondary circuit danger of shock is eliminated, but serious interruption of service may result if the transformer insulation fails. The insulation difficulty is particularly great in potential transformers the primary winding of which, consisting of many turns of fine wire, is subjected to the full P.D. between phases. Potential transformers constitute one of the weakest features in a modern h.t. installation.

and a secondary winding with a greater number of turns supplies a correspondingly reduced current to the instrument circuit. The secondary may be threaded directly on to the main circuit conductor itself which then forms, in effect, a single turn primary. If the secondary circuit is to be opened whilst the main current is flowing, the secondary terminals of the transformer should first be short-circuited, otherwise a dangerous P.D. will be produced between them when the circuit is opened.

Potential transformers are step-down transformers, the secondary winding consisting of a few turns whilst the primary is a high-resistance winding of many turns connected between the main-circuit conductors.

Subject to a correction allowing for the fact that not all the magnetic flux produced by the primary winding passes through the secondary winding (§ 35), the ratio of an instrument transformer is the ratio of the number of primary to secondary turns. The question of magnetic leakage is, however, covered by stating the corresponding values of primary and secondary current or pressure as the case may be. Thus a 5 000 / 5 current transformer is one rated for 5 000 A primary, and 5 A secondary current; and a 6 600 / 110 potential transformer is one which yields 110 V secondary voltage when connected to 6 600 V supply. This actual ratio of the transformer is obviously what concerns the user.

For simple current or voltage measurements, accurate and constant ratio is all that is required from the instrument transformer, but if power or energy measurements are to be made by a wattmeter or watt-hour meter employing current or potential transformers (or both), it is essential that the phase relation between current and pressure in the instrument circuits be the same as that between the main current and pressure. This condition is fulfilled only if the secondary current (or pressure) of the instrument transformer be in exact phase opposition to the primary current (or pressure). The amount by which the two currents (or pressures) are not in exact anti-phase is termed the phase error of the transformer. In general, this error increases as the P.F. of the main circuit decreases, and increases also as the load on the secondary of the transformer increases. For this and other reasons, the advice of the maker should be sought before connecting a number of instruments, etc., to one transformer.

For current or voltage measurements the ratio error of the transformer is alone important; for power factor measurements ratio error is unimportant but phase error is serious; for power or energy measurements both ratio and phase errors are important, accurate ratio being of principal importance when the P.F. of the load is high, and accurate phase being more important when the P.F of the load is low.

British Standard *current transformers* (B.E.S.A. Report No. 81) are wound to give 5 A secondary current with rated primary current, there being 23 standard ratios from 5 / 5 to 5 000 / 5 A. The two standard sizes of current transformers have rated outputs of 15 VA and 40 VA respectively at 50 cycles per sec. At these outputs the maximum permissible ratio error is $\pm$ 1 °/₀ and phase error 2° when the primary current is not less than one-fifth the rated value.* When selecting a current transformer one should be chosen with a primary current rating high enough to avoid destruction of the primary winding before the circuit is opened in event of short circuit, but not so high as to reduce abnormally the accuracy of measurement on normal loads.

In British Standard *potential transformers* the secondary pressure is 110 V when rated voltage is applied to the primary, and there are 12 standard ratios ranging from 110 / 110 to 33 000 / 110 V. The three standard sizes have rated outputs of 15, 50, and 200 VA per phase. At 110 V and approximately unity P.F. in the secondary circuit the maximum permissible ratio error is 1 °/₀ and phase error $\frac{1}{2}$° at rated or lower output. (*See also* Report, *loc. cit.*)

Additional notes on instrument transformers are given in § 384.

109. Wattmeters.—The majority of wattmeters are dynamometer-type instruments (§ 101 *b*). The main current (or a definite fraction thereof obtained by shunt or current transformer, §§ 107, 108) is passed through the stationary coil which is of low resistance, and the main voltage (or a fraction thereof) is applied to the moving coil circuit which is of high resistance. The deflection of the instrument, against the torque of the control spring, varies with the product current × voltage, *i.e.* Watts (§ 48). In order to appreciate that an instrument of this type can be used also to measure A.C. power, and to understand the conditions which must be fulfilled when so doing, it is necessary to consider the basic formulæ relating to A.C. power. This is done in § 110, and from the results there obtained it will be seen that, since a dynamometer-type wattmeter measures the mean product of pressure by current, and takes into account phase difference between the two, it is suitable in

* The phase error is likely to exceed 2° in single-turn primary transformers unless the primary current is at least 800 A or 1 200 A for the 15 VA or 40 VA transformer respectively.

principle for measuring A.C. power at any frequenc factor. Actually, however, the inductance of the causes the current in this coil (and therefore the field lag behind the applied voltage. From this cause the between the fields of the wattmeter coils is less than the main pressure and current,* and the instrument t read 'high.' On the other hand, eddy currents in fixed (current) coil cause its field to lag behind the n thus increasing the phase difference between the two instrument. The two sources of error compensate ea some extent, but the extent to which this occurs dep characteristics of the instrument and on the main circ the inductance of the pressure coil be high the current will be lower than it is assumed to be, and if instru formers be used their ratio and phase errors (§ 108 errors in power measurement. Complete investiga accuracy of A.C. power measurements is thus a compl and the risk of error is particularly great if the P.F. measured be lower than 0·5. The reading of an A.C can be checked by determining the power from the $EI \cos \phi$ (or the corresponding expression for 3-phase po the values of E and I being obtained by voltmeter an and of $\cos \phi$ by power-factor meter (§ 111). T generally gives more accurate results than the wattm P.F. of the load be low.

The *Duddell-Mather wattmeter* is a dynamomet strument designed for precision measurements. It features are: (1) The elimination of all unnecessar prevent the induction of eddy currents. (2) For the s the fixed coils are composed of insulated strands of these can be connected in various ways to alter the r instrument. (3) There are two pairs of fixed coils and of moving coils arranged astatically (§ 92 ii). (4) R taken by observing on the 'torsion head' the rotat control spring required to bring the moving system b zero line. This instrument is equally suitable for D. A.C. of any frequency up to 350 cycles per sec. It can

* Assuming that the main-circuit current *lags* behind the vo main current be *leading* with regard to its voltage, inductance in coil of the wattmeter tends to make he instrument read 'low.'

measure A.C. power at very low P.F., *e.g.* the dielectric loss in cables the P.F. of which is about 0·02 (§ 312).

The remarks made in § 101 *b* concerning the weak field of dynamometer-type ammeters and voltmeters apply also to wattmeters of this type. If the coils be provided with iron cores, the fields are greatly increased (§ 43) and greater working forces can be obtained. This is particularly desirable where recording instruments (§ 93) are concerned. The use of iron cores in D.C. wattmeters is subject only to the objection that hysteresis errors are introduced (§§ 34, 100), but in A.C. wattmeters the errors of the ordinary air-core dynamometer wattmeter—particularly the phase errors—would be prohibitive if the coils were simply provided with iron cores. Specially arranged *iron-cored wattmeters* have been devised by Drysdale, Sumpner, and others for use on A.C. circuits.*

Induction wattmeters can be used only for A.C. power measurements. The principle employed by these instruments is identical with that of induction ammeters and voltmeters (§ 102), except that the torque on the disc is produced by two electromagnets, one excited by the main-circuit current (or a fraction thereof) and the other by the main-circuit voltage. The torque on the disc varies with the power to be measured and is opposed by a controlling spring. These instruments are very suitable for use on switchboards.

The measurement of 'wattless power' is discussed in §§ 110, 116.

110. Power and Energy Measurement in A.C. Circuits.—As explained in § 29, the *average* value of an alternating current or pressure is zero, and the effective value of the wave is the *root mean square* (R.M.S.) ordinate. The instantaneous power in a single-phase A.C. circuit equals the product of the corresponding instantaneous values of pressure and current, and if the pressure and current waves are not in phase the power curve is an alternating wave (§ 56). Whereas a negative (reversed) current is exactly equivalent to a positive current as regards heating (§ 29), a negative value of instantaneous power means that power is being returned to the supply circuit. It is therefore the *average* (and *not* the R.M.S.) value of the power wave which is the measure of

* For details see *Industrial Electrical Measuring Instruments*, by Edgcumbe, pp. 219 *et seq.*

its effective value. It can be shown that the average value of the power is given by—

(i) *Single-phase Circuits*—

Average Power = R.M.S. Volts × R.M.S. Amperes × Power factor

i.e. $W = EI \cos \phi$.

(ii) *Three-phase Circuits* (if symmetrical and balanced)—

Average Power = $\sqrt{3}$ × R.M.S. Volts between phases × R.M.S. Amperes per phase × Power factor.

i.e. $W = \sqrt{3}\, EI \cos \phi$.

In a dynamometer type wattmeter (§ 109) the torque on the moving system is at every moment proportional to the instantaneous value of the power and may be negative during part of the cycle. The inertia of the moving system causes it to take up

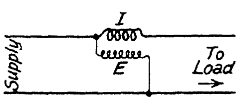


FIG. 15.—D.C. or single-phase A.C. wattmeter.

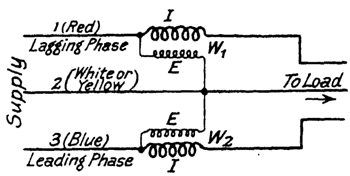


FIG. 16.—Measuring 3-phase power (balanced or unbalanced load) in 3-phase, 3-wire circuit by two wattmeters.

the position corresponding to the mean value of the torque and thus to indicate the average power.

A.C. Wattmeter Connections.—The connections for a *single-phase* wattmeter are identical with those for a D.C. wattmeter. The common terminal of the pressure and current coils should be on the supply side (*see* Fig. 15). The power indicated is then greater than that supplied to the load by the amount of power expended in the current coil, but this is of little practical importance. If the pressure coil were connected on the load side of the current coil the power indicated would be greater than actually supplied to the load by the amount of power expended in the pressure coil. This again is of little importance in commercial power measurements, but if a watt-hour meter be connected in this way, it will record continuously the energy consumption of the pressure circuit; there is necessarily an expenditure of energy in the pressure circuit so long as the instrument is connected to

the supply, but this is not charged to the consumer if the meter be connected as in Fig. 15 because the current for the pressure coil does not then pass through the current coil.

Alternative methods of measuring 3-*phase power* are represented in Figs. 16-18, the conditions applying to each being stated below the diagrams; these methods are applicable also to watt-hour meters (§ 115). The *two-wattmeter method* is applicable to balanced or unbalanced loads in 3-phase, 3-wire circuits. The current coils of two wattmeters are connected in two of the phase conductors (directly or through shunts or instrument transformers, §§ 107, 108), and the pressure coils are connected between these phases and the third phase. The total power supplied to the load is the algebraic sum of the readings of the two wattmeters. If the readings of the two instruments be W_1 and W_2 watts, the

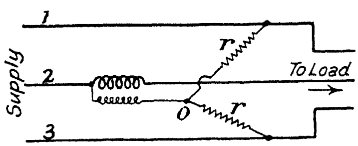


FIG. 17.—Measuring 3-phase power (balanced load) in 3-phase, 3-wire circuit by one wattmeter.

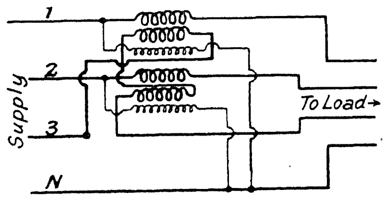


FIG. 18. — Measuring 3-phase power (balanced load) in 3-phase, 4-wire circuit by two wattmeters.

ratio of these readings is $m = W_1 / W_2$ and the P.F. ($\cos \phi$) of the load may be calculated from the expression—

$$\cos \phi = \frac{m + 1}{2\sqrt{(m^2 - m + 1)}}.$$

This formula holds good only if the load be balanced, but the two-wattmeter method of measuring power is applicable whether the load be balanced or not, and whatever the power factor. Another form of the same expression is—

$$\tan \phi = \sqrt{3}\,(W_1 - W_2) / (W_1 + W_2).$$

If $\tan \phi$ be calculated from this formula, the corresponding value of $\cos \phi$ is most easily found by reference to trigonometrical tables.

If the power factor be less than 0·5 one wattmeter will reverse and its connections must be interchanged in order to obtain

a positive reading; the *difference* between the readings of the two instruments is then the power supplied to the load.

Instead of using two independent wattmeters, two wattmeter elements may be mounted on a common spindle. The resultant deflection is then the algebraic sum of W_1 and W_2 provided that the connections are correct. Where a two-element wattmeter or watt-hour meter is used it is, of course, impossible to determine the power factor from the readings of the instrument.*

In a *balanced* 3-phase system the power (or energy) can be measured by a *single wattmeter* (or watt-hour meter) by connecting the current coil in one phase and the pressure coil between that phase and the neutral. This measures the power in one phase, and the total power is three times as great. If the neutral is not available an 'artificial neutral' can be obtained by connecting two resistances of suitable value as in Fig. 17; the relation between these resistances and the impedance of the pressure coil must be such that O is the true neutral point. Alternatively, the current coil may be excited by current transformers in two phases connected differentially, the pressure coil being connected across these two phases.

The power in a 3-*phase*, 4-*wire circuit* must be measured by three wattmeters if the load be *unbalanced*, each instrument having its current coil in one phase conductor and its pressure coil between that phase and neutral. If, however, the load be *balanced* the connections shown in Fig. 18 may be used. This arrangement resembles the 2-wattmeter method (Fig. 16), but the two pressure coils are connected to the neutral, and each of the current coils is opposed by a current coil connected in the phase which has no pressure coil.

Wattless Component.—The difference between apparent power (VA) and true power (W) in any A.C. circuit is often called 'wattless power.' This term, though descriptive, is contradictory, and it is better to refer to the quantity in question as the wattless component, idle component, or reactive component of the apparent power. The value of the wattless component is the *vector*

* Where two *separate* watt-hour meters are used to measure the energy consumption of a balanced load it is possible to calculate the P.F. by the formula given above, or, if one of the instruments fails to register, it is possible to calculate what its record should be from the reading of the other meter provided that the average P.F. is known.

difference between IE (the apparent power) and $IE \cos \phi$ (the true power); its value is $IE \sin \phi$ and, just as $\cos \phi$ is termed the 'power factor' (§ 56), so may $\sin \phi$ be termed the 'idle-power factor' or the 'reactance (or condensance) factor.' The importance of the wattless component of total power is explained in Chapter 5. Methods of measuring it are:—

(i) By ammeter, voltmeter, and P.F. meter, the value of $\sin \phi$ corresponding to the measured $\cos \phi$ being found from trigonometrical tables, and the value of $EI \sin \phi$ being then found by multiplication.

(ii) A dynamometer-type wattmeter (§ 109), connected with its pressure and current coils 90° out of phase, measures the product $EI \sin \phi$. With a centre-zero scale the instrument shows whether the wattless component is lagging or leading. Similarly, an induction wattmeter can be reconnected to indicate $EI \sin \phi$. (*See* also § 116 iv.)

111. Power Factor Indicators or Phase Meters.—The power factor of a single phase A.C. circuit is the cosine of the angle of phase difference between the pressure and current waves (§ 56), and equals the ratio of true power to volt-amperes (apparent power) in the circuit. The same definition is applicable to the P.F. of a 3-phase system in which the phase voltages are equal and the loads balanced. In the case of an unbalanced 3-phase system the P.F. may be different in the several phases and the definition and determination of the mean P.F. becomes a matter of difficulty. For most practical purposes it is sufficient to take as the P.F. of an unbalanced 3-phase system the value indicated by a 3-phase power factor meter or the value calculated from the ratio: True power / Volt-amperes.*

The numerical value of the power factor is the same whether the current lags or leads with regard to the line voltage by a given angle ϕ, but lagging current has a much worse effect on regulation than leading current. On ordinary commercial circuits the load current almost invariably lags, but this can be compensated by various means (*see* Chapter 5) so as to improve the mean P.F. of the system.

In order that constant watch may be kept upon this important

* Where wattless-component meters (§ 116) are used, this ratio may be calculated from: Mean P.F. $= W / \sqrt{(W^2 + X^2)}$, where W = reading of watt-hour meter, and X = reading of wattless-component meter.

operating characteristic it is necessary that power factor indicators should be employed. It would be tedious and inefficient always to calculate the P.F. from the readings of ammeter, voltmeter, and wattmeter (§§ 56, 109) or from the readings of two wattmeters (§ 110), though both of these methods are occasionally useful. (*See also* § 91.)

The principle generally employed in power factor indicators is that of using two magnetic fields, respectively in phase with the main current and voltage, to determine the position of a moving system the spindle of which carries a pointer moving over a scale calibrated in values of cos ϕ.

The operation of the Everett-Edgcumbe *single-phase P.F. indicator* may be explained by reference to Fig. 19. The fixed coil I is traversed by the main current (or fed by current transformer, § 108). The moving system, which has no control (§ 90), consists of two coils AB mounted at right angles on the spindle which carries the pointer P. The coil A is in series with resistance R, and B is in series with a condenser C; an inductance may be used instead of the condenser, but it is not then possible to get so nearly 90° phase difference between the currents in the two coils. When the P.F. of the main circuit is unity the current I is in phase with that in A, therefore this coil lies parallel to the coils I. At zero power factor in the main circuit, the current I is in phase (or 180° out of phase) with the current in B which leads 90° with regard to the voltage E, hence the coil B sets itself parallel to the coils II, the pointer being then horizontal and pointing to the left if the main current be lagging, and to the right if the main current be leading. For intermediate values of P.F. the pointer takes up a position intermediate between these extremes. At unity and zero power factor the position of the pointer is independent of frequency, but the division of current between A and B varies with frequency, hence the reading at intermediate values of power factor is affected by frequency and this instrument must be calibrated for the frequency on which it is to be used.

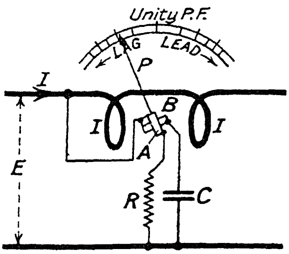


FIG. 19.—Single-phase power factor meter.

For 3-*phase systems* two different instruments are used ac-

cording to whether the load is balanced or unbalanced;* the general principle of operation is, however, the same as already described. The instrument for use on *balanced* 3-phase systems embodies a fixed coil, carrying the main or transformed current of one phase, and three pressure coils attached to a pivoted spindle which carries the pointer. Each of the three coils has one end connected through a resistance to one of the phases, the other ends being joined up together to form a neutral point. Three-phase currents flowing in these coils induce a rotating field, and the system will set itself in such a position that, at the moment the current in the fixed coil reaches its maximum value, the field due to the moving system lies along its axis. In the instrument for *unbalanced* 3-phase loads, three fixed coils are employed, one on each phase; the moving system then takes up a position corresponding with the *average* power factor of the main circuit, while each phase can, if desired, be separately tested by means of a short-circuiting plug. Both the 'balanced' and the 'unbalanced' 3-phase P.F. indicators are unaffected by changes in voltage, temperature, frequency or wave form.

The Nalder-Lipman *moving-iron* power factor indicator for *single phase* and for *polyphase balanced or unbalanced* loads is characterised by the fact that the moving system consists only of thin iron vanes carried by a spindle which is built up of magnetic and non-magnetic portions. Two sets of fixed coils are employed, *viz.* the 'field' coils energised by the line currents, and the 'magnetising' coils energised by the line voltage (through transformers in both cases if the load exceeds 30 A at 650 V). The 'field' (current) coils are placed with their axes parallel to each other and in separate planes. The iron vanes lie in these planes and are set at angles corresponding to the phase displacement of the currents in the phases of the main circuit (90° and 120° for the 2-phase and 3-phase instruments respectively). The

* The requirements for measuring the P.F. of a polyphase system are as follows:—

	Coils required *With Balanced Load.*	Coils required *With Unbalanced Load.*
For a 2-phase or 4-phase circuit	*Either* 2 current and 1 pressure *or* 1 current and 2 pressure.	2 current and 2 pressure.
For a 3-phase circuit . .	*Either* 3 current and 1 pressure *or* 1 current and 3 pressure.	3 current and 3 pressure.

'magnetising' (pressure) coils magnetise the corresponding vanes of the moving system periodically and in correct sequence, and the vanes are subject to the directive pulsating magnetic forces produced by the 'field' coils. For every value of main circuit P.F. there is a position of the moving system in which the latter is in equilibrium; this position is indicated by the pointer and forms a measure of the power factor. The readings are unaffected by changes in current, pressure, or temperature and, over a wide range, by changes in frequency or wave form. Since no current has to be carried into the moving system, the latter is quite free from control and the scale is a complete circle (360°). Leading and lagging power factors are indicated respectively in the right- and left-hand quadrants of the upper semi-circle and in the diametrically opposite quadrants of the lower semi-circle. The direction of current flow determines in which of two opposite quadrants the pointer stands for any particular P.F. The connections are such that the pointer is in the upper semi-circle when the power flow is forward, *i.e.* from generator to line. In interconnecting or 'tie' lines the power flow may be in either direction.

Values of P.F. commonly found in practice are given in § 157.

Phase rotation indicators are discussed, together with *synchroscopes*, in connection with the paralleling of generators (§§ 148, 149).

112. Frequency Meters.—One method of determining the frequency of an A.C. supply is to use the alternations of the latter to set in vibration a number of metal reeds of known and graduated natural frequencies; that reed, the mechanical frequency of which corresponds to the frequency of the A.C. supply, is set into vigorous, resonant vibration and thus indicates the frequency in question. A number of other frequency meters utilise in one way or another the fact that the reactance of an inductance (§ 44) or the condensance of a capacity (§ 46) varies with the frequency of the current passing through them; this characteristic, which makes the accuracy of some instruments dependent upon constant frequency (*e.g.* the single-phase P.F. indicator, Fig. 19, § 111) can be used as a measure of frequency. The associated principle of electrical resonance (§ 47) is also employed.

For testing purposes a frequency meter may need a wide

range of measurement (say from 15 to 100 cycles per sec. for commercial supplies), but under working conditions the periodicity of any particular A.C. supply varies but little, and an open scale with a range of a few cycles per sec. (say from 47 to 53 cycles) is required. In the absence of a frequency meter, the frequency of supply can be calculated from—

$$\text{Cycles per sec.} = \left\{\begin{array}{l}\text{Revs. per sec. of al-}\\ \text{ternator or } \textit{synch-}\\ \textit{ronous} \text{ motor.}\end{array}\right\} \times \left\{\begin{array}{l}\text{No. of } \textit{pairs} \text{ of poles}\\ \text{in the alternator or}\\ \text{motor.}\end{array}\right\}$$

Reed-type Frequency Meter.—A number of steel springs of different natural frequencies (*i.e.* miniature tuning-forks) are mounted parallel to the core of an electromagnet which is excited from the circuit, the frequency of which is to be measured. One end of each spring is fixed and the other is bent inwards so as nearly to touch an iron disc attached to one end of the magnet core. All the reeds are thus subjected to a periodic attraction, the frequency of which is *twice* the frequency of the supply current (because each half wave produces an attraction). That reed, the natural frequency of which equals twice the frequency of the A.C., vibrates in resonance and its bent-over end appears as a radial white line; the other reeds remain nearly or quite stationary. Against each reed (or every fifth reed) there is marked on the scale the supply frequency corresponding to resonance of that reed.

It is sometimes useful to know that the range of a frequency meter of this type can be doubled by polarising the magnet (by a D.C. winding or a permanent magnet) so as to neutralise the effect of alternate half-waves of the A.C. The number of attractions on the reeds is thus halved and the frequency corresponding to the resonant reed is twice that shown by the scale.

The *Weston frequency meter* works on a different system. In this instrument there are two fixed coils each made up of two sections wound flat, of which one is slipped inside and at right angles to the other. The movable system consists of an iron needle, a pointer, and a single vane air damper, no control springs being required. The connections are shown in Fig. 20. The fixed coils are in series across the line with a reactance X_1 in series with one and a resistance R_2 in series with the other; a resistance R_1 is in parallel with the former and a reactance X_2

with the other. The whole combination is then in series with a further reactance X. The circuits as shown form a balanced Wheatstone bridge (§ 120) at normal frequency, but any change of frequency is accompanied by a corresponding shift of the resultant field of the fixed coils, which is indicated by the pointer on an open scale.

In the *British Thomson-Houston frequency meter* a curved iron core is excited by a coil connected to the A.C. supply. A moving coil is connected to a condenser and is so pivoted that it can move along the curved iron core towards or away from the fixed coil. The moving coil acts as the secondary of a transformer (the fixed coil being the primary) and it always sets itself so that its inductance, which varies with the position of the

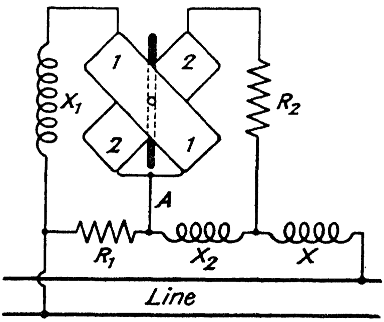


FIG. 20.—Diagram of Weston frequency meter.

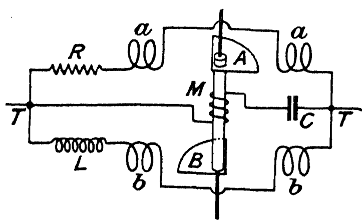


FIG. 21.—Diagram of Lipman-Nalder frequency meter.

coil along the core, and the capacity of the condenser to which it is connected are in resonance (§ 47) with the supply frequency. Harmonics in the supply wave have little effect on the flux threading the moving coil, hence the instrument is practically unaffected by wave form; neither is it affected by wide variations in supply voltage. The moving coil carries a pointer which moves over a scale calibrated in frequencies. If the frequency be constant the instrument can be calibrated to measure inductances or capacities connected in the circuit of the moving coil.

The *Wild frequency meter* uses two electromagnets, the winding of one being of high inductance and low resistance, and that of the other being of low inductance and high resistance. The two windings are connected in parallel and the current through the inductive circuit varies inversely with frequency,

whilst that through the other circuit is practically independent of frequency (§ 44). In the air gaps of the two magnets lie the diametrically opposite sector-shaped blades of an aluminium vane which is mounted on a spindle without control. The position of the vane, and therefore of the pointer, depends solely on the relative flux produced by the two magnets which, in turn, depends only on the supply frequency. The instrument is connected in series with a choking coil which smooths out harmonics and makes the readings practically independent of wave form.

The *Nalder and Thompson* (*Lipman*) *frequency meter* depends on the fact that the P.F. of a circuit containing inductance and capacity varies widely with change in frequency round about the value of frequency for which the circuit is in resonance (§ 47) The P.F. of such a circuit can thus be made a measure of frequency. The instrument described is broadly similar to the Lipman P.F. meter (§ 111), but the connections are such that the position of the pointer varies with the P.F. of the magnetising circuit of the instrument itself. Referring to Fig. 21, the supply of which the frequency is to be measured is brought to the terminals TT, between which there are three parallel paths through the instrument. The branch Ra is of high resistance and low inductance, whilst the branch Lb is of high inductance and low resistance. The vanes AB on the spindle are thus subjected to magnetic fields differing practically 90° in phase. The magnetising coil M surrounds the spindle (which is of magnetic material between A and B), and the inductance of M and capacity of C are such that this circuit is in resonance at, say, 50 cycles per sec. At higher frequencies the inductance of M preponderates and the current lags behind the E.M.F. producing it. At lower frequencies the current leads with regard to the E.M.F. Thus the phase of the field produced by M, and polarising the vanes AB, varies with the frequency (which does not, however, affect the phase of the fields produced by aa and bb). The position taken up by the moving system thus depends only on the phase of the field produced by M, *i.e.* upon the frequency of the supply connected to TT. The range and form of the scale can be varied by altering the electrical characteristics of the instrument circuits or the setting of the iron vanes.*

113. Supply Meters.—Though these instruments are also used

* *See also Electrician*, Vol. 87, p. 458.

to measure the total energy supplied to feeders, etc., the usual function of supply meters is to measure (directly or indirectly) the energy supplied to individual consumers, thus providing the basis on which to charge for the supply. The energy (kWh) supplied to a D.C. circuit is $(EIt / 1\,000)$ kWh; to a single-phase A.C. circuit $(EIt \cos\phi) / 1\,000$ kWh; and to a 3-phase circuit $(\sqrt{3} \cdot EIt \cos\phi) / 1\,000$ kWh, where E = D.C. voltage or voltage between A.C. phases; I = line or phase amperes; t = time of flow of this current in hours; and $\cos\phi$ = P.F. of A.C. circuit. Thus to measure the true energy supplied we need a meter which takes into account E, I, t, and $\cos\phi$; such an instrument is a *watt-hour meter* (§ 115). The degree of constancy in the voltage of commercial supply is, however, such* that E may be assumed to be constant; on this assumption, *and if* $\cos\phi$ *be constant* in the case of A.C. supply, the true energy supplied is proportional to the product $I \times t$, *i.e.* an *ampere-hour meter* (§ 114) may be calibrated to indicate directly in kWh *at stated voltage*. If the actual voltage differs from the declared value the error in the kWh-indication of an ampere-hour meter is proportional to the difference between the actual and declared voltages.

Watt-hour meters record the actual energy supplied whatever the voltage variation, but they involve a pressure circuit in which there is a continuous dissipation of energy, whether the consumer is taking current or not. The energy dissipated in the pressure circuit is not recorded by the meter (*cf.* Fig. 15, § 110) and represents a serious loss to the supply authority if many such meters are installed on the premises of small consumers. Ampere-hour meters avoid this loss and are simpler and cheaper in construction; on the average the true voltage is likely to be below as often as it is above the declared value, but this is always a point of possible contention. Ampere-hour meters give no measure of A.C. energy unless the power factor of the load (as well as the voltage) is constant; this assumption is justified only in the case of a load consisting entirely of filament lamps, non-inductive heating apparatus, etc. With the increasing use of electric motors for domestic appliances there is less opportunity for using ampere-hour meters in A.C. systems.

---

* The statutory limit of variation is ± 4 % from declared voltage up to 3000 V and $\pm 12\frac{1}{2}$ % if the declared voltage exceeds 3000 V. The declared frequency (cycles / sec) must be maintained constant within $\pm 2\frac{1}{2}$ %.

Electrolytic meters measure ampere-hours by the amount of electro-chemical action produced in an electrolyte (§ 28), but are applicable only to D.C. measurements. In motor meters a spindle geared to a recording train carries a driving disc which is subjected to a torque varying with the load current (in ampere-hour meters) or with the watts (in watt-hour meters). The spindle is also subjected to a braking torque which varies with the speed of rotation of the spindle. When the meter is running steadily the driving torque is equal to the braking torque, *i.e.* the speed of rotation varies with the load current or watts. The total revolutions of the meter spindle therefore vary with ampere-hours or watt-hours, as the case may be, and are recorded by a train of clockwork which is calibrated in Board of Trade units (kWh).

The indications in the majority of meters are shown on a series of dials, for units, tens, hundreds, etc., actuated by a train of wheels ; and it is not difficult for the inexperienced to make a mistake in reading, as the hands are seldom in exactly their correct positions.

For example, if the dials in Fig. 22 be read from left to right the result might be taken as 3 209. If, however, the reading is taken (as it should be) *backwards from the unit dial* the correct result will be seen to be 4 199, a very different matter; the last figure is evidently 9; the next hand points almost to 0, and therefore the last two figures must be 99. Obviously, therefore, when we come to the hundred dial the hands must be indicating just *short* of 200, *not* nearly 300, so we have 199. The hand on the thousand dial is pointing nearly to 4 000, but the previous figures show that it should actually be *over*, not *under*, 4 000 ; *i.e.* 4 199, not 3 199. A mistake in meter reading does not always matter seriously; in the instance here given, a reference to the reading of the previous month would generally show up the error at once, for if the average consumption were (say) 220 to 550 units a month, the previous correct record would be 3 979 or 3 649 units, as the case may be, *i.e.* higher than the false reading, which must therefore necessarily be wrong. If, on the other hand, the false reading gave too many units, the following month's correct reading would give negative consumption, and the error would be detected.*

To save time in reading meters and to reduce the risk of error to a minimum, there has recently been perfected a special type of miniature camera, which is applied to the meter window by the inspector, and then photographs the complete dial plate of the instrument by electric light furnished by dry cells and a glow-lamp included in the equipment. The negative thus obtained is used by the clerical department in making out the consumer's bill, and it is even suggested that a photo-print might be attached to the bill. There is nothing impracticable

* To bring home these remarks it may be added that a reviewer of the first edition of this book (*Engineering*, 2 Nov., 1917, p. 476) stated that the author's own reading was incorrect; neither diagram nor text has been altered, however, except for italics.

in this system of 'meter-reading,' but every supply engineer must decide for himself whether it is worth while employing it, under the particular conditions of supply and office organisation in the supply area concerned.

Meters are often provided with cyclometer dials, giving the indications in plain figures. In the earlier types these were apt occasionally to slip a notch and give a reading 10, 100, or 1 000 units in excess; such a mistake could only be detected by the comparison of one month's consumption with another, and not always by this method. As the actual reading of a meter is, in the absence of fraud, taken to be 'conclusive proof' of the con-

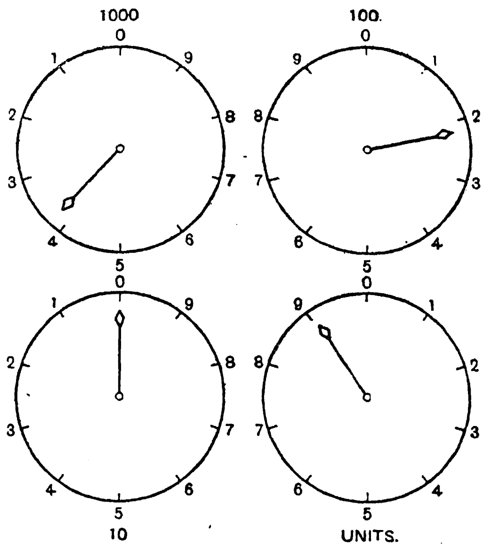


FIG. 22.—Illustrating the misleading effect of errors in the setting of hands on meter dials.

The correct reading of the dials shown is 4199.

sumption indicated, this source of error was a dangerous one. Manufacturers claim to have cured the defect, but there may still be early batches of these meters in use; the cause appears to have been due to the gear wheels being only friction-tight on the spindles; they should always be rigidly attached, so that when once accurately set they cannot alter.

Electrolytic meters are simple in construction, and have no moving parts and therefore no friction error; no current can pass through the electrolyte without producing its share of electro-

chemical action, and no current passes through the meter when the consumer's circuits are open. Periodic re-setting of the measuring chamber, etc., is required but this is a minor disadvantage. Electrolytic meters are unsatisfactory in very hot climates; they have been known, when disconnected entirely from the circuit, to record a very large consumption of energy (90 kWh in one day) owing to temperature effects at about 110° F. Any commutator-type motor meter is subject to more or less error due to variable friction and electrical resistance between brushes and commutator; automatic brush-shifting gear is often employed so that the contact surfaces used when the meter is on very light load are kept in perfect condition.

The principal features of various types of meters are mentioned in the following paragraphs; for detailed information reference must be made to special treatises (§ 125). Meter testing is discussed in Chapter 40.

114. Ampere-hour Meters.—The quantity of electricity supplied to a circuit can be determined by a current-actuated device, time being taken into account by measuring the total effect produced. Thus in electrolytic meters the amount of electrolyte decomposed, or of metal electro-deposited, is a measure of ampere-hours whilst in a motor meter the total revolutions of the spindle form the desired measure.

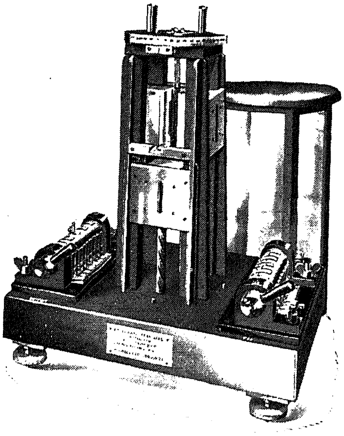
Electrolytic Meters.—The Bastian electrolytic meter employs nickel electrodes in a solution of caustic soda, the level of which falls as the gaseous products of electrolysis escape. A layer of paraffin prevents evaporation, and the level of the electrolyte is read against a scale which is calibrated in kWh (§ 113). The pressure drop in this meter is 2 or 3 V which is prohibitive where heavy current circuits are concerned. In the Wright shunted electrolytic meter about $\frac{1}{200}$ of the main current passes through the meter and the pressure drop is 1 V or less. A solution of a mercury salt is used as electrolyte and mercury is transferred electrolytically from a reservoir of mercury (forming the anode) to an iridium cathode, whence it runs into a tube calibrated in B.O.T. units. Electrolytic meters with copper electrodes and copper sulphate solution as electrolyte can be used conveniently as prepayment meters, the consumption of the prepaid quantity of electricity and the consequent opening of the circuit pending a further payment, being determined either by the increase in weight of

the cathode or by the dissolving of the anode (the latter being in strip form and fed into the solution in proportion to the payment made).

Motor Meters.—In these meters the current to be measured passes through an armature which lies in the field of a permanent magnet. In the mercury motor meter current flows radially through a copper disc mounted on the spindle and immersed in a shallow chamber filled with mercury; a magnetic field perpendicular to the disc is produced by a permanent magnet. Alternatively, the armature is bell-shaped, current flow therein being parallel to the spindle, and the armature rotating in an intense radial field. Eddy-current braking (*cf.* damping, § 90) is provided in this, as in all other types of motor meters, and when it is necessary to compensate for the fact that the fluid friction in the mercury chamber rises more rapidly than is desired with increase of speed, this is done by using an auxiliary coil to increase the driving field.

Commutator-type meters have an armature winding similar to that of a D.C. motor with the important exception that the meter armature has no iron core. The winding may be drum-shaped or it may be flat and enclosed by an aluminium casing which reduces windage, protects the windings, and acts also as braking disc. In order that the armature may be wound with fine wire, meters of this type are generally shunted; the p.d. across the shunt is about 1 V at full load. The field is produced by permanent magnets.

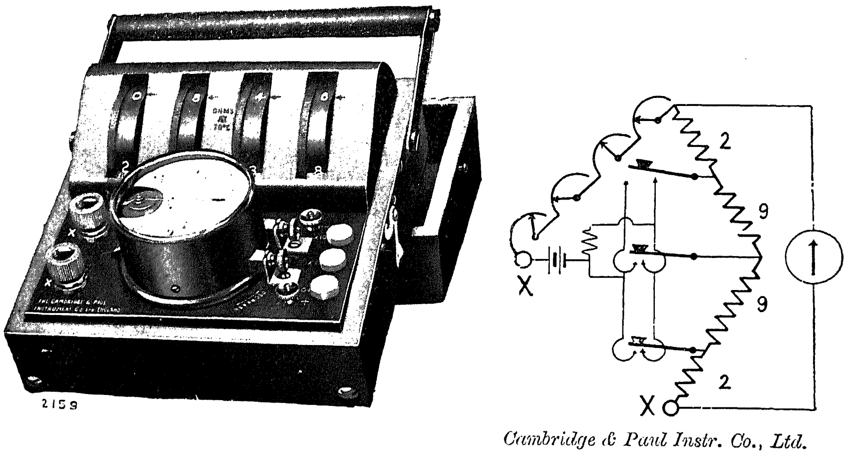
Any motor-type ampere-hour meter with permanent magnet field is reversible according to the direction of the current so that if the current is first going through the coils in one direction, as when charging a battery, and then in the opposite direction, as when discharging the battery, the instrument will show the difference between the ampere-hours passed through it in the two cases. Ampere-hour meters used in this way on electric battery vehicles (Chapter 36) to indicate the state of charge of the battery are calibrated in ampere-hours (standard dial ranges being up to 100 or 500 Ah). The pointer rotates clockwise on discharge and counter-clockwise on charge, and stands at zero when the battery is fully charged. To allow for the fact that the Ah-input on charge is necessarily greater than the Ah-output on discharge (Chap. 18), the meter is arranged to read correctly, on discharge,



H. Tinsley & Co.

THE DRYSDALE WATTMETER.

This instrument can be calibrated on D.C., and will then read accurately on D.C., or single- or three-phase A.C. circuits. Metal parts are eliminated wherever possible, and the windings are stranded to reduce eddy currents. The two systems of the wattmeter are arranged at right angles so as to have no interaction; if desired, one system can be used with D.C. and one with A.C. For tests at very low power factor (*e.g.* on cables or condensers) the current through one set of coils can be increased, so as to magnify the deflection.

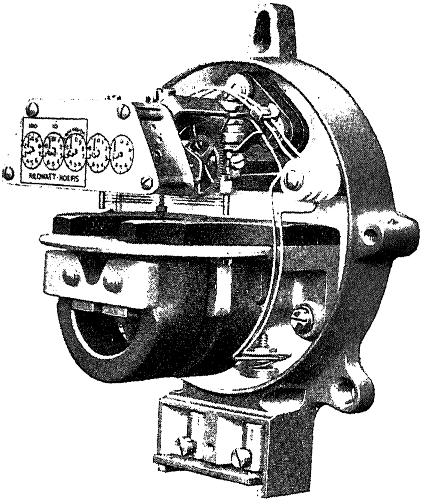


Cambridge & Paul Instr. Co., Ltd.

SELF-CONTAINED ROTARY PATTERN WHEATSTONE BRIDGE.

The set is complete with dry battery, and the only connection required is that of the unknown resistance to the terminals XX. The 'Unipivot' galvanometer requires no accurate levelling. Measurements can be made, accurate to 1 in 500, over the range 0·01 to 11 110 ohms. The rheostat arm is adjusted by rotating the drums shown. The value of the unknown resistance is obtained by multiplying the reading on the drums by the ratio employed (*i.e.* 0·1, 1 or 10 according to the key pressed).

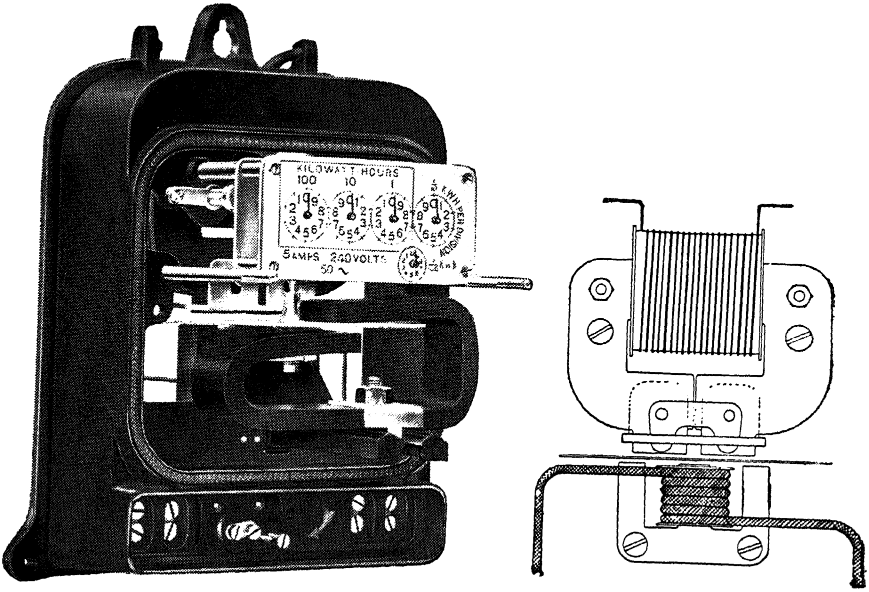
[*To face p.* 152.



D.C. Ampere-Hour Meter.

This meter is of the commutator motor type with the armature windings enclosed in an aluminium disc. The magnets are of cobalt steel. The meter starts at $\frac{1}{400}$ of full-load current and is accurate within 4 % at $\frac{1}{100}$ load, and within 2 % down to $\frac{1}{40}$ load. The speed is low, *viz.* 75 r.p.m. maximum; and the full load torque is 26 grm.-cm., and is uniform except at the points of commutation when it exceeds 32 grm.-cm. The pressure drop is less than 1 volt.

Electrical Apparatus Co., Ltd.



Ferranti, Ltd.

A.C. Watt-Hour Meter.

This meter is a single-phase instrument of the induction motor type. A shunt-wound stator is placed above, and a series-wound stator below, an aluminium rotor disc which is braked by a permanent magnet. The principal data are: Accuracy, ± 2 % from 25 % overload to $\frac{1}{20}$ load at any P.F. down to 0·5, leading or lagging. Starts at 0·5 % of full-load watts at 1·0 P.F. Rotor speed 40 r.p.m. at full load. Full-load torque 5 grm.-cm. Shunt loss 1·5 W. For unbalanced polyphase circuits two rotor discs are mounted on one spindle, each with its own stator system.

[To face p. 153.

but slow on charge by an amount which is adjustable up to 30 % according to the efficiency of the battery concerned.*

115. **Watt-hour Meters.**—The *Thomson-type watt-hour meter* is an ironless commutator-type motor, the stationary field coils of which carry the main current (or a fraction thereof) whilst the armature is connected, in series, with a suitable resistance, across the mains. The driving torque and meter speed vary with the power supplied to the load metered (*cf.* dynamometer wattmeter, § 109), a brake disc rotating between the poles of a permanent magnet. A compensating coil in series with the pressure circuit aids the field coils and produces a constant torque compensating for the (assumed) constant friction; if the meter be subject to vibration this compensating torque may cause 'creeping' (*i.e.* running on no load). This type of meter can be used for D.C. or A.C. measurements, but the mercury motor meter is more powerful and can be used on D.C. systems, whilst the induction meter is better than the Thomson type for A.C. systems.

The *mercury motor watt-hour meter* is practically identical with the ampere-hour meter of this type (§ 114) except that the field, in which the armature disc rotates, is produced by an electromagnet excited by a pressure coil. This type of meter is not suitable for A.C. measurements because of the high inductance of the pressure circuit.

The principle of action of *induction watt-hour meters* is identical with that of induction wattmeters (§ 109), and, like the latter, these instruments are not applicable to D.C. measurements. In general, the meter disc is placed between the poles of one electromagnet excited by the load current and one excited by the supply pressure (instrument transformers, § 108, being used if necessary). The current winding is of low inductance, but the pressure circuit is made as inductive as possible. An auxiliary short-circuited winding on the pressure core produces some extra lag and brings the flux of the pressure magnet into quadrature with the line voltage. The torque on the meter disc is then proportional to the load (watts) supplied. A permanent magnet embracing the disc at another place produces eddy-current braking. The moving system consists only of the disc and spindle, and two

* For the Electric Vehicle Committee's recommendations concerning ampere-hour meters for battery vehicles see *The Electric Vehicle*, Vol. 5, p. 35.

meter elements can easily be placed on one spindle for measuring 3-phase energy by the two-wattmeter method (§ 110).

The *Aron (pendulum) watt-hour meter* employs two stationary solenoids, traversed by the load current, to accelerate and retard respectively two pendulums, the "bobs" of which are coils of fine wire connected, in series with each other and a suitable resistance, across the supply voltage.* The difference between the rates of oscillation of the pendulums is proportional to the power supplied, and the energy (Wh) is recorded by a train driven from the two pendulums through a differential gear. The spring driving the pendulums is wound electrically and difference between the natural periods of the pendulums is neutralised by reversing every 10 mins. the recording gear and the current through the pendulum coils. Though rather intricate and costly in construction, these meters are precision instruments; provided that the inductance of the pressure circuit is low, they can be used for A.C. measurements. The winding gear of the A.C. meter must, however, be adapted to the frequency of supply concerned.

Though theoretically independent of voltage changes, any watt-hour meter should be used on approximately the pressure for which it is designed, otherwise the torque will be unduly low (low voltage); the pressure winding will be overheated (high voltage); or the pressure flux will not be proportional to the voltage where iron cores are used.

116. Special Supply Meters.—Many instruments come under this heading, but those of general interest are as follows:—

(i) *Prepayment Meters.*—Any meter can be made to operate on the prepayment principle by adding to it a mechanism which closes a switch in the main circuit when a coin is inserted, and opens the circuit automatically when the amount of energy corresponding to the prepayment has been consumed. The trip gear is actuated from the recording train, and a further payment is required to restore supply after interruption. The electrolytic (copper strip) meter is a popular type (§ 114).

(ii) *Two-rate Meters.*—Any meter can be provided with two recording trains and a change-over device operated electromagnetically under the control of a time-switch. The consumptions recorded on the two trains are charged at different prices (§ 272).

* Where the load is heavy, the pendulums may carry shunted current coils, the pressure coils being then the stationary ones.

(iii) *Summation Meters.*—These are used to measure the total energy supplied by a station or through a number of circuits. Each machine or 3-phase circuit may have its own pressure and current circuits in the meter operating on the two-wattmeter principle (§ 110), a number of such elements operating on one disc and several discs being mounted on one spindle; the mechanical effects of each meter are thus added together. Alternatively, the addition may be effected on the electrical side, a current transformer in, say, the No. 1 phase of each machine or feeder being connected to a pair of bus bars which serve the current circuit of the summation meter. The latter is then an ordinary induction meter (§ 115), the pressure circuit of which is excited by the appropriate phase of the system (No. 1 phase in the case assumed).

(iv) *Wattless Component Meters.*—These are likely to assume great importance as the practice of power-factor correction (Chapter 5) and of penalising low-power factor (§ 274) becomes more general. A dynamometer or induction-type watt-hour meter can be re-connected to integrate the product $EI \sin \theta$ (§ 110) thus measuring the wattless kVA supplied. The charge to the consumer is then based on the readings of a watt-hour meter and a wattless kVA meter, or on the reading of a watt-hour meter and the mean P.F. of the load as calculated from the readings of the two meters (§ 111). For further information on meters for measuring wattless or total power *see El. Rev.*, Vol. 87, pp. 452, 505.

117. Maximum Demand Indicators.—The importance of the maximum power demanded in any consumer's circuit is explained in § 260. Just as ampere-hours can be taken to be a measure of watt-hours in a constant-voltage system (§ 114), so can the maximum current be taken as a measure of the maximum power demanded. An indicating ammeter with an auxiliary pointer, carried forward by the main pointer and left at the maximum deflection of the latter, would show the actual maximum current, but it is necessary to discriminate between momentary heavy current, due to motor starting, short circuit, etc., and maximum demand sustained for such period (15-60 mins.) as to preclude accidental or transitory demands. The requisite time lag may conveniently be introduced by using the heating effect of the current.

In the Wright demand indicator a heating coil wound on one bulb of a differential thermometer drives liquid into a calibrated side tube to an extent depending on the sustained maximum current. The use of a differential thermometer eliminates the effect of the general air temperature. While it is reliable as a rule, a device operating on this principle lends itself to tampering, *e.g.* by artificial cooling, when an exceptionally heavy load is required.

A maximum demand indicator described by Lincoln * operates on the thermal-storage principle and has a pointer, the deflection of which is determined by the *difference* between the heating of two bi-metal spiral springs. These springs are enclosed in capsules which are heated by resistances so connected that the difference in heating is proportional to the watts supplied in the main circuit. The maximum deflection of the pointer, during the period over which the demand is assessed, is indicated by a pilot pointer. It is claimed that this device has the same heating characteristics as the machines and cables in the supply circuit.

Another principle is to introduce heavy damping (§ 90), by glycerine or otherwise, in a current-indicating mechanism which is operated electromagnetically.

The Merz maximum demand indicator uses an auxiliary recording train and pointer to record the maximum advance of the main recording train of the meter to which it is fitted, during a predetermined period. At the end of every period (15-60 mins.), the auxiliary train is returned to zero, but its pointer is left at its maximum deflection and is not again moved forward until a higher consumption occurs during some subsequent period.

Maximum demand indicators are generally re-set quarterly when the meter is read.

118. Ondographs and Oscillographs.—The wave form of alternating current, pressure, or power can (*if constant*) be plotted by the *point-by-point method* or recorded automatically by an *ondograph* which works on this method. In either case, a disc carrying a contact pin is mounted on the shaft of the supply alternator or on the shaft of a synchronous motor driven from the supply to be investigated. A stationary contact brush touches the contact pin once per revolution, and thus connects the

* *Trans. Am. I.E.E.*, Vol. 34, p. 2 175.

supply momentarily to an indicating instrument which shows the instantaneous value of the current, pressure, etc., under investigation. By advancing the contact brush between readings, and taking a sufficient number of observations, the instantaneous values of the wave can be determined throughout a complete cycle. In the ondograph the brush is advanced automatically and a recording instrument records the successive instantaneous values; a complete cycle can thus be recorded in, say, $\frac{1}{2}$ min., by readings taken from about 1 000 successive cycles. To trace a pressure wave by the point-by-point or ondograph method, the indicating or recording instrument is connected across the supply mains; for a current curve it is connected across a non-inductive shunt (§ 107) in the main circuit; and for a power wave a wattmeter is used.

The *oscillograph* is a much simpler instrument than the ondograph and, having no appreciable lag, it is able to follow accurately all the variations in every cycle of an A.C. wave, thus providing a continuous indication or record and making possible examination of transient or non-periodic as well as periodic waves. A small mirror (actuated electromagnetically or by a hot wire or electrostatic instrument) deflects a spot of light proportionally to the instantaneous values of the quantity to be measured. The movements of the spot may be recorded on a falling or rotating photographic plate or film. Alternatively the oscillating spot may be focussed on a plane mirror which is itself oscillated by a cam on the shaft of a synchronous motor driven from the supply investigated. A second movement (proportional to time) is thus imparted to the spot which then falls on a screen and traces the complete wave form; retentivity of vision makes the moving spot appear as a continuous line. Photographic recording is alone suitable for the investigation of a particular series of waves, *e.g.* switching surges, etc.

The *Duddell oscillograph* uses a loop of phosphor bronze strip stretched in the narrow air gap of a permanent magnet or of an electromagnet with constant excitation. The instrument thus belongs to the moving-coil, permanent magnet class (101 *a*). At any moment current flowing up one side of the loop flows down the other side, and since both sides lie in the same magnetic field, one moves forward and the other moves backward (§ 33). A small mirror attached to the two sides of the loop is

thus tilted, and the spot reflected by it is deflected through a distance proportional to the current in the strip, the sensitivity being about 300 mm. deflection per ampere at a distance of 50 cm. According to the strength of the magnetic field, the dimensions of the strips, etc., the natural period of vibration is from $\frac{1}{5000}$ to $\frac{1}{12000}$ sec.; waves up to 500 cycles per sec. or even higher frequencies can be traced, and the oscillograph can be insulated for use on 50 000 V circuits.

In the *Irwin hot-wire oscillograph* the A.C. to be investigated is passed through a loop of fine wire, and a polarising direct current, fed into the centre of the loop, flows through the two halves of the latter in parallel. The resultant current in one half of the loop is the sum of the A.C. and D.C., and in the other half is the difference of the A.C. and D.C. The difference in expansion of the two sides then varies directly with the instantaneous values of the A.C. (*not* with their squares), the D.C. being constant. This difference in expansion is used to tilt a small mirror. A compensating circuit prevents any lag in the heating of the wires. No field magnets are required, hence the instrument is much smaller than the Duddell instrument; its range of applicability is practically the same.

Either the Duddell or the Irwin oscillograph can be used to trace pressure and current waves simultaneously, a fixed mirror providing a zero line and two moving systems being connected respectively across the mains (in series with resistance) and across a non-inductive shunt in the main circuit. The Irwin oscillograph can be arranged to trace a power curve if required.

Where very high pressures (up to 250 kV) are concerned, the insulation and series resistance required by current-carrying oscillographs become inconvenient or impracticable. In such cases and even at lower pressures (down to 5 kV) the *electrostatic oscillograph* offers advantages. The principle employed is identical with that of the electrostatic voltmeter (§ 103), a phosphor bronze or steel strip or strips oscillating in an electrostatic field produced between plate electrodes connected to the pressure under investigation, this motion being imparted to the mirror which reflects the indicating spot of light. Currents of 1 mA or less can be recorded by connecting the instrument across a non-inductive shunt which must, however, be of very high resistance (some megohms) in order to provide a suitable operating

P.D.; such conditions arise when testing dielectrics. The electrostatic oscillograph can be used for frequencies of some thousands of cycles per sec.

The *cathode ray oscillograph* utilises the fact that a cathode ray is deflected by electrostatic or electromagnetic forces. The ray passes between two electrodes connected to the pressure under investigation, and also between field coils which impart to it a second motion proportional to time. It then falls upon a fluorescent screen where it produces a loop or polar diagram. The principal utility of this instrument is in investigating waves of very high frequency, the cathode ray having no inertia.*

119. **Measurements of Resistance.** — By an inversion of Ohm's Law (§ 17) $R = E / I$ or, in words, the resistance (ohms) of a conductor equals the potential difference (volts) between the ends of the latter divided by the current (amperes) which it produced. This law, which holds only when the three factors are unvarying, may be applied to the determination of resistances from voltmeter and ammeter readings. Referring to Fig. 23 the ohmic resistance of any conductor or winding, R (whether inductive or not), can be found by passing through R a steady D.C., the value of which is measured by an ammeter, A (reading I), whilst the P.D. across the terminals of the winding is measured by a voltmeter V (reading E); then $R = E / I\,\Omega$. The voltmeter should be of very high resistance compared with R, and it should be connected across the terminals of R; the current through V (which is included in the reading of A) is then so small as to introduce no serious error. If V were connected between B and C it would include the pressure drop in A which may be quite appreciable in comparison with that across R. This method is useful for measuring the resistance of machine windings.†

High resistances, such as insulation resistance, may be measured by applying say 440 V or 500 V to the resistance R in series with

* A convenient cathode ray oscillograph requiring an anode battery of only 300 V is described, *El. Rev.*, Vol. 91, p. 783; and a low-voltage, hot-cathode oscillograph adapted for commercial production and of great sensitiveness is described in 'The Cathode Ray Oscillograph,' by A. B. Wood, *Proc. Phys. Soc.* (*London*), Vol. 35, Pt. 2, p. 109.

† If the resistance measured between two line terminals of a 3-phase winding be R ohms, the resistance per phase is $\frac{1}{2}R$ if the winding be star-connected, and $\frac{3}{2}R$ if the winding be delta-connected.

a moving-coil voltmeter of resistance r (Fig. 24). If V be the applied voltage and v the reading of the moving-coil voltmeter, then $R / r = (V - v) / v$, therefore $R = r(V - v) / v$ ohms.

From the relation $R = E / I$ it follows that a D.C. ammeter can be calibrated to indicate resistances in ohms if the voltage applied to the resistance be constant. This amounts to dispensing with V (Fig. 23), and calibrating A to read the values of R corresponding to various currents at constant voltage V; the calibration applies only to this voltage.* If the instruments V, A (Fig. 23) be arranged so that their pointers cross, the crossing-point varies with the ratio $E / I (= R)$ and the corresponding resistance can be read on curves mounted behind the pointers (§ 91). Such a combination constitutes a true ohmeter in that it measures resistance independently of the actual values of current and voltage. The name *ohmeter* is, however, generally reserved for instruments which indicate resistance values by a single pointer

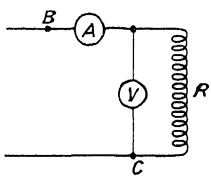


FIG. 23.—Determining resistance from ammeter and voltmeter readings.

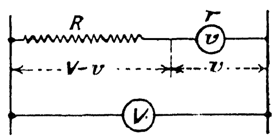


FIG. 24.—Determining resistance by voltmeter readings.

and scale, the ratio of voltage to current then being taken into account in the instrument itself. Ohmeter, ohmer, megger, and omega are trade names applied to various types of direct-reading instruments for measuring resistances. These instruments are available for measuring resistances from a fraction of an ohm up to 50 or 100 megohms on one or other of several scales, a switch determining the range. A small hand-driven magneto generator supplies the testing pressure of 200, 500, or 1 000 V. The generator

* An interesting application of this principle is in determining the salinity of boiler feed, condensate, etc. The electrical resistance of water falls rapidly as the percentage of dissolved matter increases (§ 69) and may be taken as a measure of that percentage, provided that there is only one substance, say salt, concerned. The water to be tested flows through a tube in which are two electrodes connected in series with a milliammeter across a constant supply voltage. As thus arranged, the ammeter may be calibrated to indicate directly the salinity of the water. An ohmeter, eliminating the effect of voltage variations, may be used for the same purpose.

is capable of giving only a minute current, but it is important that it should be a high-voltage machine in order that the insulation of conductors and apparatus in ordinary supply circuits may be tested at or above working voltage; high-voltage plant is tested by other means (Chapter 40). If there is poor insulation resistance so that appreciable leakage current is passed, the pressure of the magneto-generator immediately drops.

The principle of one type of ohmeter is shown very clearly by Fig. 25, this diagram being reproduced from Heather's *Electrical Engineering for Mechanical Engineers*. Two equal coils *A*, *B* are mounted at right angles, and along their common diameter is a spindle carrying the indicating pointer and (at the centre of the coils) a small soft iron bar. One coil, *B*, is connected in series with a high resistance, *R* (by varying which the range of the instrument is altered), and the other coil, *A*, is in series with

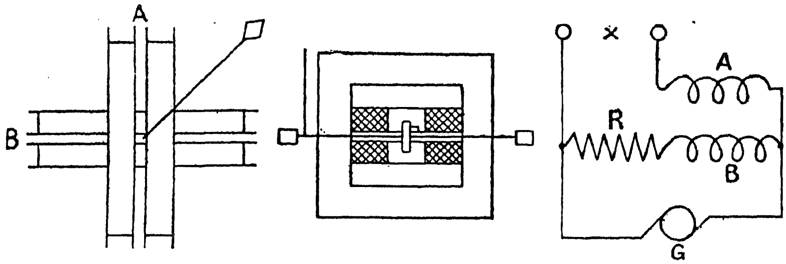


Fig. 25.—Ohmeter connections.

the unknown resistance, *X*, connected between the test terminals. The generator, *G*, is connected to the two circuits in parallel, and the distribution of current between them is determined by the relative values of *X* and *R* (*cf.* shunts, § 107). The soft iron bar on the spindle takes up a position in the direction of the resultant field produced by *A*, *B*; this position, which is indicated by the pointer, is a measure of the relative values of the currents in the coils and therefore of the resistance *X* (*R* being fixed for each range). The scale is calibrated in ohms or megohms. Though a true ohmeter, in that the readings are independent of the voltage, this instrument has weak operating forces and is affected by stray fields. These objections are overcome by using a moving-coil permanent-magnet instrument (§ 101 *a*) with two coils on one spindle, one carrying a current proportional to the pressure and the other a current proportional to the current flowing in the

resistance measured; the position taken up by the moving system depends on the ratio E / I.

The electrostatic ohmeter is an electrostatic voltmeter measuring the P.D. across a known resistance produced by the leakage current through the resistance to be measured. The polarising voltage of the instrument is the same as that used for the resistance test, hence the indications are independent of the actual voltage.

120. **The Wheatstone Bridge.**—The principle of this method, which is used in innumerable forms, is illustrated by Fig. 26. Four resistances, including x of which the value is required, are connected as shown; a and b are known as the ratio arms, and may either be of equal value; or as 1 000 to 100 or as 10 to 1; or as 1 to 10 or 100 to 1 000. The remaining arm, r, is the adjustable resistance, which is altered in value until it bears the same ratio to x as a bears to b. When this is the case the current from the battery will

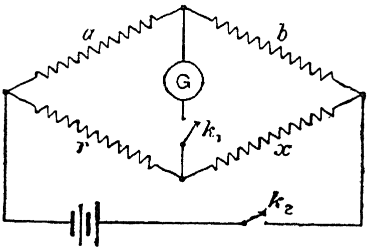


FIG. 26.—Wheatstone's bridge.

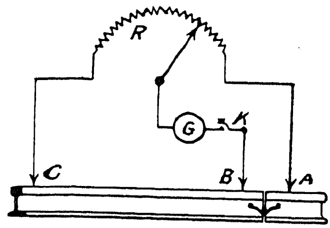


FIG. 27.—Determining resistance of rail bond.

divide up between the two parallel circuits and there will be no deflection of the sensitive galvanometer G. Keys k_1 and k_2 are provided for opening and closing the battery and galvanometer circuits; they are generally placed one below the other, so that on depressing the handle the battery circuit is closed first and opened last. The unknown resistance $x = r \times b / a$ when a balance is found, *i.e.* when there is no deflection of G. As usually made, the arms a and b consist of coils of 1, 10, 100, and 1 000 Ω, and the ratio arms actually used should be chosen of the same order of magnitude as x.

In the Post Office bridge a number of resistance coils for the arms r, a, b (Fig. 26) are mounted in a box and connected to terminal blocks on the top thereof. By removing a plug between adjacent blocks the resistance connected to those blocks is placed in circuit, and the values of the resistances are so chosen that any

resistance between, say, 0·01 Ω and 1 megohm can be measured conveniently. Portable testing sets (§ 106) frequently embody a bridge circuit arranged on this principle, but with dial switches instead of plugs for varying the resistances in circuit. One of the moving-coil instruments in the set may be used as galvanometer, and small dry cells to provide current for the bridge test may be placed in the same case. Such sets may also be arranged for resistance measurements by voltmeter or by voltmeter and ammeter readings (§ 119); great ingenuity is displayed in multiplying the functions of these sets and in reducing the risk of damaging the instruments by using incorrect combinations.

The bridge circuit shown in Fig. 27 may be used to measure the resistance of a rail-bond in terms of the equivalent length of solid rail without opening the rail circuit. Contact points *ABC* carried by, but insulated from, a rigid bar are applied to the rail as shown, and the dial-type variable resistance *R* is adjusted until the galvanometer, *G*, shows no deflection. The only current used is that flowing in the rail which should be heavy at the time of the test, the exact value being immaterial. The resistance of the bond (in terms of the length *BC* of solid rail) can be calculated by the ordinary Wheatstone bridge formula, but it is more convenient to calibrate the dial of *R* to indicate directly the equivalent length of rail.

Any bridge-circuit with non-inductive resistances can be used with A.C. to measure the resistance of electrolytes or of earth plate circuits (in which polarisation prevents accurate results being obtained with D.C.). When using A.C. the balance of the bridge may be indicated by the more or less complete cessation of buzzing in a telephone used instead of a galvanometer, or a vibration galvanometer (§ 96) may be employed.

Resistance variations as a measure of temperature are discussed in § 122; and leakage detectors in Chapter 40.

121. Measurement of Magnetic Flux.—As in the case of electric current, magnetic flux can be measured by any of the effects which it produces (*e.g.* change of electrical resistance, induction of E.M.F., or development of torque in conjunction with an electric current). The flux traversing a known cross-section having been measured the flux density (§ 40) can at once be calculated.

The electrical resistance of bismuth (§ 65) changes when the

metal is placed in a magnetic field, and the resistance of a search coil wound with this metal can be used to measure fields of 2 000 gauss or higher density. The temperature of the coil must be taken into consideration because this affects the electrical resistance and the effect of the field thereon.

If a search coil wound with copper wire be withdrawn from the field to be measured, the quantity of electricity induced in the coil varies with the strength of the magnetic field (§ 35) and may be measured by a ballistic galvanometer (§ 96) or by a Grassot fluxmeter. The latter is a moving-coil galvanometer with practically no mechanical control; the deflection varies with the linkages cut (§ 36) and is practically independent of the rate of withdrawal of the search coil.

In a moving-coil instrument (§ 101) the field is normally constant and the current in the coil is the quantity measured. For the routine testing of permanent magnets a moving-coil system may be built to suit them, each magnet in turn being applied to the movement. The latter is connected, in series, with an ammeter and regulating resistance, to a convenient supply. The current required to produce a definite deflection of the testing movement is then a measure of the strength of the magnet applied to its pole-pieces, and the ammeter in the circuit may be calibrated to indicate directly the flux produced by the magnet tested.

122. Measurement of Temperatures: Pyrometry.—Electrical methods are now used most extensively for the measurement of temperature, the property applied being either the variation in the electrical resistance of a conductor (§ 61) or the change in E.M.F. of a thermo-couple (§ 129). Any number of resistance thermometers or thermo-couples can be made to give indications or records at a control station or other central place with which they are connected by small insulated wires. A change-over switch permits a single indicating instrument to be connected to any one of any number of thermometers.

(*a*) *Resistance Thermometers.*—A resistance of platinum, nichrome, or other resistance material (§ 67) wound on a mica former and placed at the point where the temperature measurement is to be made assumes a resistance $R_t = R_o(1 + at)$ (*see* § 61) whence $t = (R_t - R_o) / R_o a$. Actually this simple relation between resistance and temperature does not apply to very wide temperature ranges, the coefficient a then changing, but for any

particular thermometer it is possible to prepare a calibration curve so that the temperature corresponding to a measured value of resistance can be read at once. With a platinum resistance, temperatures from − 200° C. to 900° C. can be read regularly, and at the risk of rapid deterioration temperatures up to 1 200° C. can be measured. It is said * that the resistance of tin varies directly with its temperature up to 1 680° C. but the metal melts about 232° C.

The mean temperature of a machine winding, etc., can easily be determined from its resistance when hot and when at atmospheric temperature. It will be found that equation (2), § 61, can be put in the form—

$$t_h = \{R_h(234{\cdot}5 + t_c) - 234{\cdot}5\ R_c\} \,/\, R_c$$

where t_h, t_c = the mean hot and cold temperatures of the winding, in °C.; and R_h, R_c = the corresponding resistances of the winding as measured by Wheatstone bridge (§ 120). Assuming the 'cold' temperature t_c to be 20° C. the above formula reduces to—

$$\text{Mean temperature } \textit{rise} \text{ (°C.)} = (R_h - R_c) \,/\, 0{\cdot}\ 003\ 93\ R_c.$$

Instead of measuring the resistance of the winding when hot and cold and calculating the mean temperature rise as above, an indicating ohmeter (§ 119) may be connected permanently in circuit and calibrated in degrees of temperature. This arrangement is applicable only to a D.C. winding (field coil, etc.), one coil of the instrument being connected in series with and the other across the terminals of the winding; the calibration then applies only to the winding concerned. Alternatively, small test coils may be placed permanently at various points in the winding, the resistances of these being measured by a bridge circuit or by an indicating instrument (calibrated in °C.). The provision of a number of resistance thermometers (or thermo-couples) at selected points in a machine- or transformer-winding makes it possible to locate and observe the hottest point and the 'hot spot temperature' with considerable precision. This is important because it is the maximum temperature attained which determines the life of the insulation (§ 80). The mean temperature rise, t_m, of a winding (as determined by resistance measurements) is, almost invariably,

* *Jour. Inst. of Metals*, Vol. 22, p. 396.

considerably less than the maximum temperature rise t_h. According to Vidmar the value of t_h is given by: $t_h = 2t_m - t_o$; where t_o = minimum temperature rise on the surface of the coil (measured by mercury thermometer).

(*b*) *Thermo-couples.*—The E.M.F. of a pair of similar thermo-couples (§ 129) connected in opposition is measured by a high-resistance instrument so that the small current flowing may not cause appreciable pressure drop (§ 24); this E.M.F. forms a measure of the hot-junction temperature if the temperature of the cold junction be constant. The voltmeter may therefore be calibrated to indicate the temperature of the hot junction. Sometimes the cold junction of the couple can be located where it is always at atmospheric temperature, the indicator scale being then set (automatically or otherwise) to suit the actual temperature of the cold junction. In other cases, the cold junction is immersed in oil in a vacuum flask.

Almost any pair of dissimilar metals will develop a thermo-electric E.M.F. (this being a possible source of error in shunts, potentiometers, etc.), but in choosing metals for a thermo-couple regard must be had to the magnitude of the E.M.F. developed, the uniformity of its variation with temperature, the constancy of the characteristics of the couple, and the temperature up to which the couple can be used. A couple consisting of a platinum wire and a wire of platinum-rhodium alloy can be used up to 1 400° C. (1 550° C. temporarily), but the materials are costly and the E.M.F. is low. Base metal couples give much higher E.M.F. but cannot be used above, say, 800° C.; this, however, covers many industrial requirements.

The approximate characteristics of various couples are given in Table 9; the values of E.M.F. are rough averages—actually, the E.M.F. does not vary linearly with the temperature, and every couple must be used with a calibration curve or with the direct-reading instrument for which it is intended.

Where practicable, couples for use at high temperatures should be sheathed for mechanical protection and to retard corrosion. Nickel-nichrome couples can be used bare for most industrial measurements up to 900° or 1 000° C.; the iron-constantan gives a higher E.M.F. and can be used up to nearly the same temperature but is subject to rapid corrosion. Copper-constantan is an excellent couple for measurements at comparatively low temperatures.

BLE 9.—*E.M.F. and Temperature Limits for Thermo-Couples.*

Couple.	Average E.M.F. Per 100° C. Difference Between Hot and Cold Junctions.	Maximum Temperature of Use for Ordinary Service.
	mV	° C.
ım—Platinum-rhodium (10 %) .	0·9-1·1	1 400
um—Platinum-iridium (10 %) .	1·2-1·4	1 000
—nickel-chromium (10 %) . .	2·0-2·4	1 000
el *—Alumel †	4·0	1 100
Constantan ‡	5·5	900
—Constantan	5·5	800
:—Constantan	5·5	400

hermo-couples make possible the measurement of temperature ıctically any point in any apparatus, and they can be made low accurately rapid variations in temperature. One indi- or a multiple recorder (§ 93) can be used with a great)er of couples. Notes on the manufacture and use of ıo-couples are given in a paper reprinted in *El. Rev.*, Vol. . 748.

) *Radiation Pyrometers* are specially useful for temperature ırements above 1 000° C. A tube pointed towards the ,ce or other hot body receives radiant energy (in amount ng with the fourth power of the absolute temperature) and nergy is focussed upon a thermo-couple the temperature of ı (generally about 100° C.) forms a measure of the high erature observed. The instrument in the thermo-couple t is calibrated to indicate the furnace temperature directly.

:) *Optical Pyrometers.*—In one useful type, a small lamp ent, viewed against the furnace as background, is made r (by increasing the current through it) until it 'matches' urnace and disappears. An ammeter in the filament circuit ibrated in degrees of temperature. In conjunction with an ption screen, this pyrometer can be used to measure eratures up to 3 000° C.

) *Magnetic Pyrometers.*—The fact that carbon-steel becomes nagnetic (§ 84) at that temperature from which it should .enched, to obtain the finest grain and best hardening in the

)0 % nickel, 10 % chromium. † 98 % nickel, 2 % aluminium.
‡ 60 % copper, 40 % nickel.

metal, has been utilised as follows: The steel is heated in an electric furnace, the heating winding of which also magnetises the metal. When the metal reaches the correct hardening temperature it becomes non-magnetic, and the collapse of its magnetic field induces a current in an auxiliary winding connected to a galvanometer or alarm-relay. With a few exceptions this method is not applicable to the hardening of alloy steels.

123. Measurement of Speed of Revolution.—Three methods of measuring speeds of revolution, which depend upon electrical apparatus and are of great service in the operation and testing of electrical machinery, utilise respectively: (*a*) the variation in E.M.F. of a magneto-generator; (*b*) the variation in frequency of a magneto-generator or a contact maker; (*c*) the stroboscopic principle.

(*a*) *Speed Measurement by Voltage.*—The E.M.F. of a constant field magneto-generator varies nearly in direct proportion to the speed at which the armature is driven. The machine is therefore direct-coupled or geared to the shaft, etc., under investigation, and the deflection of a voltmeter connected to the magneto-generator is read on a scale calibrated in revolutions per min. By using a D.C. generator in conjunction with a centre-zero moving-coil instrument (§ 101) the direction as well as the speed of rotation can be signalled at a distant point. An A.C. generator of the rotating-magnet type needs no commutator or slip rings, and the direction of rotation can still be signalled by a phase-rotation indicator (§ 150). The scale of the A.C. indicating instrument is, however, less uniform, and the power consumption is greater than that of the D.C. instrument. Special types of speed indicators and signal repeaters are made for use in ships, aircraft, and colliery winding.

(*b*) *Speed Measurement by Frequency.*—The frequency of the E.M.F. developed by an A.C. magneto-generator varies directly with the speed of the machine. It may be measured by a reed-type frequency meter (§ 112) which is calibrated to show the R.P.M. of the driving shaft or machine. Alternatively, a contact maker driven by the shaft, etc., concerned may be used to make and break a D.C. circuit which includes a reed-type frequency meter suitably calibrated. Speed measurement by frequency is exempt from error due to weakening of generator magnets.

(c) *Stroboscopes.*—If a disc bearing any geometrical pattern (except a concentric circle) be mounted on the shaft of a synchronous motor and illuminated by an arc lamp connected to the same supply as the motor, the disc will appear to be stationary because, at the moments of maximum illumination from the arc, the pattern on the disc is always in one of two definite positions relative to the poles of the motor if the latter is a two-pole machine. If the motor has more than two poles the pattern is seen successively in a series of definite positions; the apparent form of the pattern is changed but, as seen, the pattern is stationary. If, however, the motor driving the disc be an induction motor the pattern seen will revolve slowly backwards (*i.e.* in the direction opposite to that of the motor revolution), the apparent speed of the pattern being the difference between the synchronous speed of the motor and the actual r.p.m. of the rotor. This difference is the 'slip' of the machine (Chapter 28). The principle involved in both the cases mentioned is that of determining an unknown speed by matching or comparing it visually with a known speed or frequency; the identity of or difference between two speeds can thus be determined with great accuracy over a wide range of values.

Instead of using the fluctuating light of an A.C. arc as the basis of observation, an electrically-operated tuning fork carrying a shutter may be used to open and cover a narrow slit through which is viewed a disc marked with a concentric series of toothed circles. If there be n glimpses through the slit per sec., and if there be N teeth in the ring which appears stationary, it is clear that the disc makes $(1/N)$ of a revolution in $(1/n)$ sec., *i.e.* the speed of rotation is n/N revs. per sec.*

Special stroboscopic discs are supplied which assume different geometrical patterns at known speeds, so that from the appearance of the disc and the apparent direction and speed of its rotation it is possible to determine the actual speed over a wide range, with almost perfect accuracy and without taking any power from the machine under test. The relation between speed and time can be determined very accurately by pressing the key of a recording chronograph when the stroboscope indicates known speeds.

* If there be a larger ring containing $2N$ teeth this will also appear stationary, hence the above calculation must be based on the smallest ring which appears stationary.

Another application of the stroboscopic principle is to the apparent arresting or slowing down of high-speed motion or cyclic events for examination at leisure. For instance, if an A.C. arc be viewed through a narrow slot in a disc driven by an induction motor connected to the same supply, the slip of the motor will cause the arc to be seen at a later moment in each succeeding cycle. If the motor has p pairs of poles and n °/₀ slip, the disc will make $(100-n)/np$ revs. before the same point in the cycle of the arc is again seen. In other words, if a 2-pole motor with 2 °/₀ slip be used, one cycle of the arc will (apparently) be drawn out to occupy $(100-2)/2 = 49$ revs. of the disc or about 1 sec. assuming 50-cycle supply. By retentivity of vision (as in a kinematograph picture) the 49 glimpses of as many consecutive cycles will appear as one slow cycle accurate, unless there are differences between successive actual cycles or unless irregularities occur between the points 'glimpsed' (such irregularities may be detected by reducing the slip of the motor, thus increasing the number of glimpses per cycle).

The principle explained in the previous paragraph is employed in the Elverson 'oscilloscope' or 'slowing-down' lamp. A neon lamp, mounted in a reflector which screens the observer from direct rays, is switched in circuit by a contact maker driven from the machine observed. If the flash is produced at the same point in successive cycles of the machine's operation the machine appears to be stationary. If, however, a creeper gear be used to advance the phase of the flash by $\frac{1}{100}$ rev. per revolution of the machine, then glimpses from 100 actual revolutions appear as one slow revolution. There is, in fact, an 'optical gear ratio' making the machine appear to run at $\frac{1}{100}$ of its actual speed. By this device the conditions at a particular point in the cycle of operation or the events of a complete cycle can literally be seen under the actual working conditions of the machine. Aero engines, gear teeth, chains, dynamo brushes, and in fact the parts of any machine, whether in rotation or translation, can be examined and vibration can be located and analysed.

124. Relays.—The function of a relay is to control the opening or closing of one or more circuits if and when predetermined conditions arise, such as current overload, reverse power, etc. In delicacy of construction and accuracy of operation relays are

comparable with instruments, and they are generally made by instrument makers. A relay to control or be operated by a certain electrical quantity generally works on the same principle as an instrument designed to measure that quantity; indeed, the relay is often identical with the measuring instrument except that the indicating pointer and scale of the latter are replaced by a contact arm moving between fixed contacts. The functions and applications of the more important types of relays are considered in Chapter 15.

125. Bibliography.—(*See* explanatory note, § 58.)

STANDARDISATION REPORTS, ETC.

B.E.S.A. Reports.

No. 37. Specification for Electricity Meters.

No. 81. Specification for Instrument Transformers.

No. 89. Specification for Indicating Ammeters, Voltmeters, Wattmeters, Frequency and Power Factor Meters.

No. 90. Specification for Recording (Graphic) Ammeters, Voltmeters, and Wattmeters.

No. 107. Rolled Sections for Magnet Steel.

BOOKS.

Industrial Electrical Measuring Instruments. K. Edgcumbe (Constable).

Electrical Measuring Instruments and Supply Meters. D. J. Bolton (Chapman & Hall).

Electricity Meters. C. H. W. Gerhardi (Benn Bros.).

Electricity Meters. H. G. Solomon (Griffin).

Testing of Electricity Meters. S. James (Chapman & Hall).

Oscillographs. J. T. Irwin (Pitman).

Pyrometers and Pyrometry. Ezer Griffiths (Pitman).

PART II.—GENERATION: PRIME MOVERS: SALE OF ELECTRICAL ENERGY.

CHAPTER 4.

GENERATORS AND THEIR ACCESSORIES.

126. Sources of Electrical Energy.—Electricity being a form of energy it cannot be 'generated' in the strict sense of the word, but can only be obtained by conversion from some other form of energy. It is desirable that this fact should be realised, but having emphasised it, we may follow universal practice by speaking of electric 'generators' and the 'generation' of electrical energy without qualification. Probably every form of energy can, by appropriate means, be converted into electricity, the losses incidental to the conversion varying with the initial form of energy and with the method of conversion employed. The principal sources and methods known at present are discussed in the succeeding paragraphs; they are:—

(i) Electro-chemical generators or primary cells.
(ii) Thermo-couples.
(iii) The piezo-effect.
(iv) Electrostatic generators.
(v) Dynamo-electric or electromagnetic generators.

Of these well-defined types only the electro-chemical and dynamo-electric generators are of any importance as sources of electricity for lighting, power, and similar commercial purposes; and for all but weak currents, or under special circumstances, dynamo-electric generators are alone employed. Without dynamo-electric machines electrical engineering, as we know it, would be non-existent, but the other sources of electricity are of definite importance.

127. Electro-Chemical Generators: Primary Batteries.—Although the terms are used somewhat indiscriminately, a 'battery' more properly consists of a number of single 'cells' connected together—each cell consisting of two plates or elements

of dissimilar substances (one electro-positive to the other, *vide* Table 10) in a bath of ' electrolyte ' which has a chemical affinity for one or both of them. Between the two plates there will then be a fixed difference of potential, and if they are connected together externally, a current will flow in the circuit in accordance with Ohm's Law (§ 17 as modified in § 21). The electrical energy generated is due to chemical change in the elements and is proportional to it in amount.

Conversely, a current from an external source will cause chemical changes to take place in a similar arrangement of plates and electrolyte, as in an electroplating bath and the like. On this latter principle elements are obtained from their compounds by 'electrolysis'; and accidental electrolysis, from leakage currents, or currents using ' earth ' as a path, may also have a destructive effect on water pipes or the lead sheathing of wires and cables.

The distinction between primary cells and secondary cells (Chapter 18) is as follows: The component parts of a primary cell are assembled in the form in which they are used, and then yield electrical energy as the equivalent of chemical action which proceeds until the active elements are consumed; the cell is then exhausted and must be more or less completely rebuilt with fresh materials. In a secondary cell, on the other hand, the plates are 'formed' and brought to a suitable state of dissimilarity by passing electricity through the cell, which is then said to be 'charged' and is capable of yielding a current by reversal of the chemical changes effected during the charging operation. When discharged, a secondary cell can be recharged as before, and the cycle can be repeated until the plates disintegrate or become deteriorated by permanent chemical action.

The practical applications of primary cells are restricted to weak current services—such as bell ringing, portable flash lamps, alarm and signal circuits, etc.—unless the convenience of electricity and the absence of any other source thereof justify the abnormally high cost of producing it by chemical means. The electro-positive element or 'anode' (generally zinc) is dissolved away in the electrolyte in proportion to the ampere-hours generated (§ 28), and the electro-negative element or ' kathode ' (commonly copper or carbon) generally remains unaltered. The two elements constitute a galvanic ' couple.' The conventional direction of the current is from the anode, through the electrolyte, to the kathode and thence back to the anode through the external circuit; the zinc or electro-positive element will therefore be the negative pole of the cell and the electro-negative carbon or copper will be the positive pole in a ZnC or ZnCu cell. In an electrolytic cell (*e.g.* a plating vat) the anode is similarly the plate through which the current enters the electrolyte and the kathode is that by which the current leaves the same.

Table 10 represents the electro-chemical series of certain metals, in which those occurring at the head of the list are said to be electro-positive relatively to those lower down; the farther apart in the list the metals chosen, the higher the E.M.F. produced.

TABLE 10.—*Electro-chemical Series of Metals.*

1. Potassium.	7. Cadmium.	13. Copper.
2. Sodium.	8. Nickel.	14. Mercury.
3. Magnesium.	9. Cobalt.	15. Silver.
4. Manganese.	10. Lead.	16. Platinum.
5. Zinc.	11. Tin.	17. Gold.
6. Iron.	12. Bismuth.	18. Antimony.

The E.M.F. developed in a primary cell composed of any two of these elements in a suitable electrolyte is proportional to the heat of formation of the resulting compound.

Various types of primary cell are made according to whether a considerable steady current is required or merely an occasional momentary current, as for electric bells, and so forth. In a cell of the original type devised by Volta, the electrodes are zinc and copper, and the electrolyte is dilute sulphuric acid; when such a cell is in use it 'polarises' rapidly owing to hydrogen collecting on the copper, thus increasing the internal resistance of the cell besides establishing a back E.M.F. which reduces the E.M.F. available at the terminals. In the Daniell cell the zinc anode is in sulphuric acid contained by a porous pot, the latter being immersed in an outer vessel containing the copper kathode and a solution of copper sulphate; copper instead of hydrogen is liberated at the kathode of this cell, polarisation is eliminated, and the E.M.F. remains so nearly constant (at 1·1 V) that the cell can be used as a standard cell (§ 128) for rough standardisation tests. The bichromate or Fuller cell uses zinc and carbon electrodes with sulphuric acid as active electrolyte and potassium bichromate as depolariser; this cell has high E.M.F. (2·2 V) and low internal resistance, and is therefore suitable where relatively heavy current is required. The Leclanché cell uses zinc and carbon electrodes in an electrolyte of sal-ammoniac, with manganese dioxide as depolariser round the carbon; when suitably constructed this cell is capable of maintaining relatively heavy current for long periods, but the ordinary porous-pot type polarises quickly; the

E.M.F. is about 1·45 V per cell. So-called 'dry' cells are of the Leclanché type with only sufficient water added to render the paste between the electrodes a reasonably good conductor; the internal resistance is much higher than that of the wet-type cell, and whereas the latter deteriorates very slowly on open circuit,* a 'dry' cell becomes exhausted by 'local action' within a few weeks or months of its being moistened, even though no current be taken for an external circuit.

128. Standard Cells.—For the accurate determination of electric pressures 'standard cells' are used, these being primary batteries whose potential difference at any temperature is very accurately known; practically no current is drawn from them, the E.M.F. being merely balanced against a known proportion of the E.M.F. to be determined (§ 95). The Clark standard cell consists of zinc and mercury, in an electrolyte of mercurous and zinc sulphate. Its E.M.F. is 1· 432 8 V at 15° C. decreasing by 0· 083 °/₀ per 1° C. rise of temperature. The Weston normal standard cell, which is now more generally used, employs cadmium amalgam instead of zinc and cadmium sulphate instead of zinc sulphate. The E.M.F. is 1· 018 3 V at 20° C. and the temperature coefficient is almost negligible, *viz.* 0· 004 °/₀ per 1° C.

It is important to note that a standard cell should be regarded as a generator of known E.M.F. and not as a source of current. It should be used only to calibrate potentiometers (§ 95), no current flowing through the cell when balance is established. During the process of balancing, the cell should be in circuit for as short a time as possible because it is subject to appreciable polarisation, and its E.M.F. (on open or balanced circuit) then differs from standard until depolarisation has been effected; this may take hours if much current has passed through the cell.

129. Thermo-couples.—If two wires of different metals be joined at their ends and one junction be hotter than the other there is produced a thermo-electric E.M.F. which sends a current round the circuit so long as the temperature difference between the two junctions is maintained. Many attempts have been made

* The zinc gradually becomes encased by crystals which should be scraped off, the clean metal then being re-amalgamated with mercury. The porous pots increase in resistance from a similar cause and the depolariser becomes exhausted; the pots may be 'revived' to a considerable extent by soaking them for 24 hrs. in weak hydrochloric acid (1 part commercial acid to 5 parts water).

to utilise this property for the direct conversion of heat to electrical energy, but the practical difficulties are great and apparently insuperable. The E.M.F. is low, say 5 mV per 100° C. difference in temperature between the junction as an average (§ 122), hence an enormous number of couples are required in series to produce even 100 V; similarly, an immense number of such groups must be coupled in parallel to give any commercially useful current. The cost of assembling and maintaining the couples is high and, finally, the overall efficiency is low because, although the losses of the steam engine or turbine are avoided (§ 166), the absorption of heat by the hot junctions is of indifferent efficiency and the heat conducted along the couples must be lost by radiation or removed by artificial cooling of the cold junctions. Though there seem to be no prospects for thermo-couples as generators of electricity for commercial purposes, they are most valuable in pyrometry (§ 122). Thermo-electric E.M.F. is also important as a possible source of error in measuring instruments and circuits (§ 107).

130. **Piezo-Electric Effect.**—The application of mechanical pressure to crystals of certain substances—among them tourmaline, quartz, and fluorspar—on diametrically opposite faces parallel to the major axis of the crystal, sets up a P.D. between the faces perpendicular to those on which the mechanical pressure is applied. This phenomenon offers a means of obtaining small known charges of electricity for purposes of research on radioactivity, atomic structure, etc. It has been suggested * that the converse phenomenon, *viz.* mechanical distortion of the crystal by the application of a P.D. to its faces, is partially responsible for the gradual deterioration of high-tension porcelain insulators in service. The piezo-electric effect is of no present importance as a means of obtaining a continuous flow of electricity. It has been utilised in the measurement of high pressures † (in guns, etc.) up to 50 000 lbs./sq. in. Applications of the piezo-electric effect to microphones and gramophone reproducers are described in 'Commercial Piezo-Electricity,' E. W. C. Russell and A. F. R. Cotton. *El. Rev.*, vol. 92, p. 284.

131. **Electrostatic Generators.**—It is well known that when two dissimilar substances are rubbed together they become electrified; for instance, the vulcanite cap of a fountain pen, after

* W. D. A. Peaslee, *Jour. Amer. I.E.E.*, Vol. 39, p. 447.

† Bureau of Standards, Scientific Paper No. 445.

being rubbed on dry cloth, will pick up fragments of paper by electrostatic attraction. This phenomenon is applied to the production of very weak current at high voltage in the *frictional machine* which consists of a disc or cylinder of glass rotated between rubbing pads of soft leather; the charge produced on the glass is drawn off by metal combs. Greater quantities of electricity can be produced with greater ease and certainty by *influence machines*, of which the Wimshurst pattern is the best known, though not the most efficient. The principle employed in influence machines is that of rotating two carrier plates about a spindle placed between two fixed plates. The fixed plates are given small initial charges of opposite polarity (by friction). With the carrier plates temporarily connected electrically to each other and placed adjacent to the fixed plates, the positive fixed plate induces a negative charge on the carrier near it, and the negative fixed plate induces a positive charge on its carrier. The positive charge repelled from the first carrier is neutralised by the negative charge repelled from the second carrier. The connection between the carriers is now broken, leaving isolated positive and negative charges upon them, and the spindle is turned through half a revolution thus bringing the carriers to the similarly charged fixed plates to which they add their charge. By multiplying the number of fixed and moving plates and perfecting the mechanical details influence machines have been constructed which need 1 h.p. or more to drive them and which yield an output of several milliamperes at a pressure in the neighbourhood of 500 000 V (sufficient to break down a 12-14 in. air gap). Modern influence machines find applications in electro-therapeutics, X-ray production, electro-culture (Chapter 33), testing materials, electrostatic separation and precipitation (Chapter 38), etc. In his book on the subject (§ 152), V. E. Johnson estimates that the efficiency of the best influence machines is about 45 %, and states that there is no theoretical reason why the efficiency should not be as high as that of dynamo-electric generators. The same author describes a $\frac{1}{8}$ h.p. electrostatic motor of his own design and construction. Though it is improbable that electrostatic generators and motors can ever compete with high-power electromagnetic machines, their development should not be overlooked.

132. Dynamo-Electric or Electromagnetic Generators.—

The dynamo-electric generator—usually termed a 'dynamo' or 'generator'—is a machine for converting mechanical power into electrical power, through the medium of electromagnetic induction (§ 35); to be effective, it must be driven by mechanical power, *viz.* steam, gas, oil, water, or other; this is converted by electromagnetic induction into electrical energy. The broad principle on which the working of generators is based will be seen from Figs. 28 and 29 from the late Professor Thompson's *Elementary Lessons in Electricity and Magnetism.*

These figures are identical except as regards the arrangements for collecting the current. In both a coil of conducting wire, which may have any number of convolutions, is so placed that it can be rotated between the north and south poles (N, S) of a permanent steel magnet; in so doing the coil cuts across the lines of magnetic force, which run from pole to pole, and an E.M.F. is consequently induced in the coil. The latter (the armature or

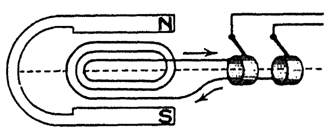


FIG. 28.—Diagrammatic representation of electric generator, with current collection from slip rings.

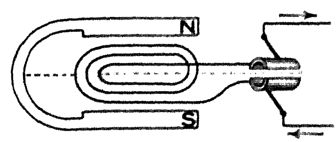


FIG. 29.—Diagrammatic representation of electric generator, with current collection from commutator.

rotor) in the figure is supposed to be spun around the longitudinal dotted axis, the upper portion coming *towards* the observer. The arrows then show the direction of the induced current in the wire, assuming that there is a closed electrical circuit, between the ends of the external wires, in which the current can flow. If there is no such circuit an E.M.F. is nevertheless induced, tending to cause a current to flow in the same direction; but as the resistance is infinite the current is nil. When the coil is at right angles to the position depicted, it is neutrally placed with respect to the poles of the magnet, and for the moment no E.M.F. is induced and no current flows; thereafter the part of the coil that was under the influence of the north pole comes under that of the south pole, and *vice versa*, so the direction of the E.M.F. (and of the consequent current in the coil, if any) reverses. This reversal happens twice in each revolution, so that an 'alternating' current (§ 11) is invariably generated *in the coils.**

* This statement does not apply to homopolar generators (§ 137).

Herein lies the distinction between Figs. 28 and 29. In the former the two ends of the coil of wire are connected to two independent metal contact rings, each with a collector or 'brush' rubbing against it, so that the alternating current is led away as it is generated to the external circuit. These two rings will alternately be + and − at each half revolution of the coil. In Fig. 29, however, there is a single contact ring, or commutator, split horizontally, and revolving with the coil, with fixed brushes rubbing on it above and below; at the moment the wave of current in the coil has died down to zero, as explained above, the brushes cross the gap in the ring and consequently reverse their connections to the ends of the coil. The connections of the armature coil to the external circuit are reversed simultaneously with the reversal of current flow in the armature winding, so that the alternating current in the coil is commuted into a unidirectional or rectified current (§ 13) in the external circuit. The top brush will then be always positive and the lower brush negative. It must be remembered that *relative* motion of the magnet system or 'field' and the coil system or 'armature' is essential; consequently, if the coil is stationary and the magnet is revolved around it in the opposite direction, precisely the same results will follow; both methods are in fact used.* In actual generators used for power purposes the permanent magnet is replaced by an electromagnet or a number of electromagnets (§ 32), while a series of armature coils replace the single coil; and the two-part commutator (in a dynamo) is replaced by one with many segments, corresponding with the number of coils. Each coil then in turn generates its own wave, which is rectified by the corresponding segments of the commutator, and the result is that all the separate waves of current overlap, and the succession of waves of rectified alternating current becomes a continuous current, as explained in §§ 13, 14.

The term 'dynamo' is generally reserved for direct or continuous current generators (Fig. 29), machines which deliver

*Though the direction of a magnetic field and the direction of flow of a current in a conductor are matters of convention (§§ 32, 127) there is a definite relation between the conventional directions of field and current and that of the relative motion between the field and the current-carrying conductor. Professor Fleming's rule or mnemonic for the determination of the third of these factors when any two are known is stated in § 35.

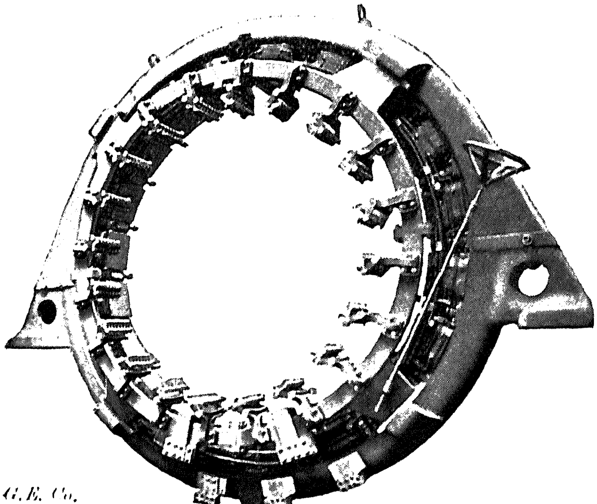
alternating current to the external circuit (Fig. 28) being termed 'alternators.'

Reversibility of Generators; Motors.—In theory, and for the most part in practice also, an electric generator is reversible, and can be used also as a motor.* In the two diagrams of a simple dynamo and alternator above, if continuous or alternating current (as the case may be) is supplied to the brushes from an external source the coils will revolve. The current creates a magnetic field around the coil (§ 32), which is under the influence of the steel magnet, and the tendency of the coil is then to set itself at right angles to the poles of the steel magnet. But the reversal of the direction of the current by the commutator in the one case and by the natural alternation in the other case, occurs just at the right moment to cause the coil to make another half turn; and so on indefinitely. By increasing the number of coils this primitive machine is converted into a practical motor. While the coil is thus revolving in a magnetic field, an E.M.F. is generated in it by induction, *opposing* the applied or impressed E.M.F. of the circuit as mentioned in § 35; this is called the back- or counter-E.M.F. (Chapter 28).

133. **Component Parts of Generators.**—From the preceding paragraph it will be seen that, according to the method of current collection, the same machine can theoretically be used as either a continuous-current generator or an alternating-current generator, and this is actually done in the case of the rotary converter (Chap. 17). As a rule, however, the general arrangement of D.C. and A.C. generators is different for reasons stated below. In a dynamo the magnets are fixed and the drum of rotating coils (wound on a laminated iron core), in which current is induced, is called the 'armature.' The wave of current is rectified by the 'commutator,' which is a cylindrical body, mounted on the shaft of the armature and revolving with it, consisting of a large number of radial conducting bars insulated from one another, but electrically connected to the coils of the armature winding. The 'brushes' make contact with the commutator, as shown in Fig. 29 (§ 132), collecting and conveying the current to (or, in the case of motors, from) the external circuit.†

* Sometimes, as in balancing motor-generator sets, the two functions are intentionally combined in a single machine, which is working at one moment as a motor and the next as a generator (Chapter 20).

† Carbon brushes are now employed almost universally because they facilitate sparkless commutation. In practice there are many coils on the armature and a corresponding number of bars in the commutator. The width of the brush is limited (for reasons of commutation) to that of two or three commutator bars and, as the current-carrying capacity of carbon is low (§ 66), it is generally necessary to use two or more brushes on each spindle, *i.e.* on each line of current collection from the commutator. To prevent the brushes from wearing grooves in the commutator they are staggered so that their tracks overlap. If there are more



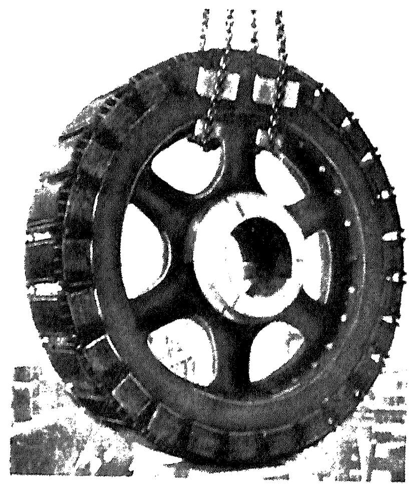
G.E. Co.

FIELD FRAME AND BRUSH GEAR FOR LOW-SPEED D.C. GENERATOR.

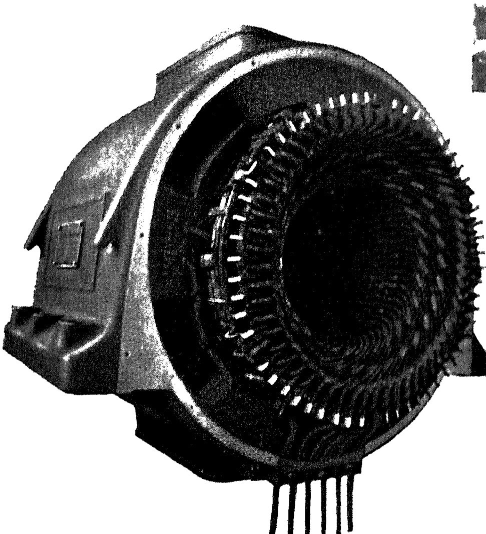
This generator is rated at 1 150 kW, 220 V, 115 r.p.m., and is driven by a gas engine working on blast furnace gas.

ROTATING FIELD FOR LOW-SPEED ALTERNATOR.

This rotor is driven at 115 r.p.m. by a gas engine working on blast furnace gas. The stator output is 1 200 kVA at 440 V, 3-phase, 25 cycles / sec.



General Electric Co., Ltd.

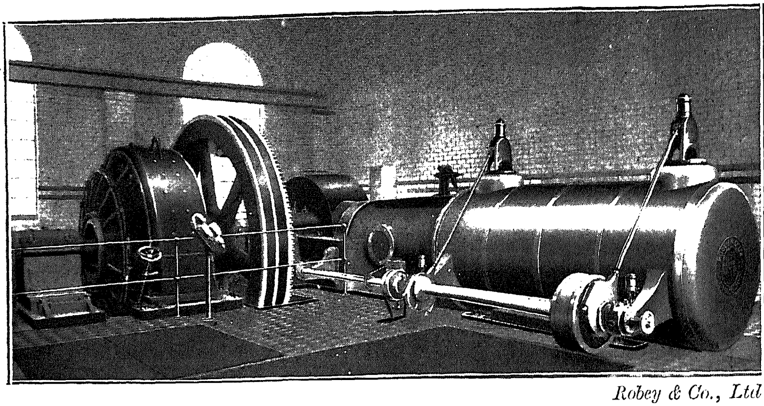


STATOR FOR HIGH SPEED TURBO ALTERNATOR.

The rating of this machine is 6 000 kVA at 6 600 V, 3-phase, 50 cycles, and the rotor is driven at 3000 r.p.m. The illustration shows clearly the method of supporting the end windings.

General Electric Co., Ltd. (London)

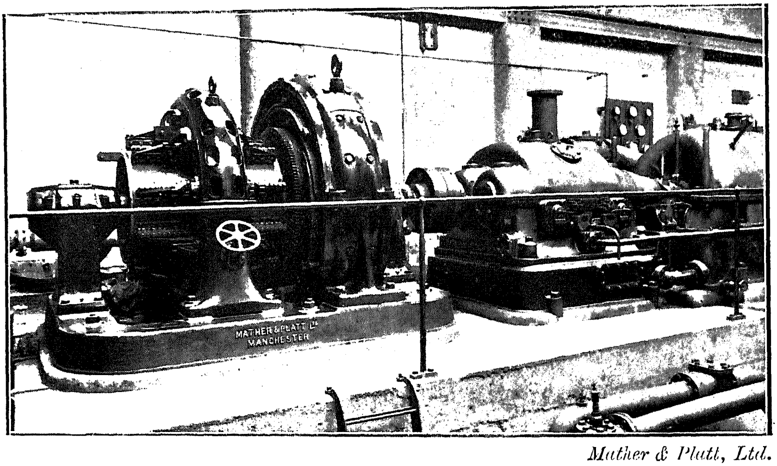
[*To face p.* 180.



Robey & Co., Ltd.

1 100 I.H.P. 'Uniflow' Engine Direct-coupled to a D.C. Generator.

In the 'uniflow' engine the whole range of expansion of the steam from boiler pressure to condenser pressure is effected in a single cylinder. The steam flows from the inlet valves at each end of the cylinder to the exhaust ports at the centre and never in the reverse direction, hence the live steam does not come in contact with surfaces cooled by the exhaust. This greatly reduces condensation losses and it is claimed that the 'uniflow' engine is as economical as a triple-expansion engine.



Mather & Platt, Ltd.

D.C. Generator Driven through Gearing from a Steam Turbine.

Geared turbines are now used extensively to drive A.C. or D.C. generators of from 500 to 2 500 kW capacity. The main advantage in A.C. installations is that the turbine can be run at much higher speed, and can therefore be designed more efficiently, than if direct coupling were employed. For D.C. work there is the additional advantage that the generator can be designed on ordinary lines, avoiding the mechanical and commutation difficulties associated with high speeds. The illustration shows a generator rated at 500 kW, 125 V, 4 000 A, and particular attention is called to the large commutator and separate yoke for the brush gear needed to deal with this heavy current.

[*To face p.* 181.

The system of electromagnets in a generator, with their energising coils, creates the magnetic 'field,' and the coils are called the field 'winding' or 'field magnets.' The exciting or field current may be obtained from the armature of the generator itself in the case of a D.C. machine (§ 138) or a separate 'exciter' dynamo may be used (§ 140); in the former case the machine is 'self-excited,' in the latter 'separately excited.' Alternators are necessarily separately excited. The use of interpoles is discussed in § 139.

In an alternating current machine the fixed part is called the 'stator,' and the moving part the 'rotor'; either may consist of the field system or of the coils in which the current is induced, but it is generally more convenient to place the alternating current windings on the stator, continuous current being then led to the field coils on the rotor through slip rings.

A 'slip ring' or 'collector ring' is a plain conducting ring, revolving with the shaft, for effecting (by means of a brush) a sliding connection between a fixed conductor and a revolving conductor (Fig. 28). Slip rings are used for conveying continuous current to a revolving magnet or for conveying alternating current to or from a revolving armature. In a D.C. or A.C. motor the component parts correspond to those in a generator; motors are further considered in Chapter 28.

Unlike motors, generators are usually placed in dry, clean surroundings and have all the advantages of skilled supervision; it is therefore generally unnecessary to enclose them in the sense that motors are enclosed as protection against dust, moisture, etc. (Chapter 28). Where very large generators are concerned, however, the amount of heat to be dissipated from the windings is so great that the natural ventilation from an open type of construction is inadequate, and it becomes necessary to enclose the machine so that a forced current of air may be driven through it (§ 146).

134. Types of Generators and Supply Characteristics.—Classified according to the form in which electrical energy is delivered to the external circuit there are two main classes of generators, *viz.* continuous-current generators and alternating-

---

than two brush spindles alternate *pairs* of spindles and *not* alternate spindles should be staggered. Each positive brush then runs on the same track as a negative brush and uneven wear due to polarity effects is eliminated.

current generators, but each of these classes may be subdivided, according to the electrical characteristics of the types of generators available in each group. The homopolar or acyclic D.C. generator (§ 137) is characterised by the fact that it has no commutator; and series-wound, shunt-wound, and compound-wound D.C. generators (§ 138) have quite different voltage-load curves owing to the different methods by which they are excited. Alternators may be single-, 2-, or 3-phase machines; the distinction between the three types is explained in §§ 11, 15, 16.

The relative merits of continuous current, single-phase current, and 3-phase current in relation to the transmission and distribution of electricity are considered in Chapters 14 and 20. (*See also* Chapters 28 and 32.) For heating and cooking D.C. and A.C. are equally suitable (§ 29), except that A.C. supply offers the possibility of easy transformation to low pressures where required. For lighting by filament lamps A.C. of 50 cycles per sec. or higher frequency is for all practical purposes quite as suitable as D.C. supply. For power applications D.C. motors have the advantage of excellent starting and speed-control characteristics (Chapters 28, 29), and where these characteristics are particularly required it is essential to use continuous current. The total load on modern stations is, however, so great that it is economically essential to use high pressure in all but local feeders and consumers' circuits; the supply up to the consumers' premises is at not less than 3 000 V where large industrial loads are concerned. This consideration, and the fact that the pressure of A.C. supply can be changed by static transformers, whereas D.C. requires the use of rotating machinery for pressure changing (Chapter 17), has made A.C. generation and transmission standard in all new installations. Of the three main types of A.C. supply—single, 2-, and 3-phase—2-phase current offers no advantages and is not likely to be employed in any new generating plant. Three-phase current is immeasurably superior to single-phase current for general power applications, and where a simple 2-wire supply is required (as for domestic lighting, small motors, etc.), it can be taken from 3-phase mains provided that the total single-phase load is distributed reasonably uniformly between the three-phases of the main supply. In small stations the simplicity of single-phase circuits, switchboards, and instruments is a consideration, but, in this country, the majority of such stations will ultimately

become distributing centres taking supply in bulk from 3-phase generating and transmitting systems (§ 186).

The standard station pressure (§ 23) for new installations in this country are 242 V and 484 V for D.C. systems, and 457 V, 3 300 V, 6 600 V, 11 000 V, 33 000 V, 66 000 V, 110 000 V, and 132 000 V for 3-phase systems. In the latter 11 000 V is the highest pressure (between phases) for which generators are usually wound, and 6 600 V generators are usually the most economical; higher 'station pressure' is obtained by connecting transformers between generator and line.

The standard frequency of A.C. supply in this country is 50 cycles per sec., with 25 cycles per sec. as a secondary standard (§ 12); in America 60-cycle supply is used very extensively. The effects and importance of frequency are discussed in the next paragraph.

135. Effects of Frequency in A.C. Circuits.—No frequency of supply can be said to be preferable to all other frequencies; higher frequency is more favourable to some parts of a complete system and less favourable to others, hence the frequency adopted must be in the nature of a compromise. In any A.C. circuit the frequency of supply has as much effect as the voltage on the characteristics of the circuit, but whereas the voltage can be changed easily and efficiently by use of static transformers, it is rarely practicable to change the frequency. The principal effects of changes in frequency are its effect on: (1) the impedance of an A.C. circuit (§§ 44, 46); (2) the E.M.F. induced by an alternating flux; (3) the synchronous speed of generators, motors, etc.

1. *Frequency and Impedance.*—The inductive reactance of a circuit is $X_L = 2\pi fL$ ohms (§ 44), and thus increases directly with the frequency. The pressure drop due to the inductance of a given transmission line, choking coil, or other inductive apparatus, therefore, increases in proportion to the frequency. The capacity reactance on the other hand, is $X_C = 1 / 2\pi fC$ (§ 46) and, therefore, decreases with increasing frequency. The capacity of a circuit is equivalent to a negative resistance as regards pressure regulation, *i.e.* the voltage along the circuit is increased, and to an extent which increases with the frequency. When the capacity reactance equals the inductive reactance, the condition of resonance (§ 47) is established; the frequency is of equal importance with the inductance and capacity in determining the resonance. The

charging current of a transmission line (or any other condenser) increases as the frequency rises. For short distances and low voltages the higher reactance drop in transmission lines at higher supply frequencies is of appreciable importance, but in long distance, high-voltage lines the capacity effect is important, and the net voltage regulation is quite satisfactory at 60 cycles / sec. (the highest frequency used in long-distance lines).

The pressure drop due to skin effect (§ 38) increases with the sectional area and magnetic permeability of conductors, and with the frequency of supply (§ 309). It is an important factor in steel conductor rails (Chapter 35); in these, the pressure drop due to reactance and skin effect is roughly twice as great at 50 cycles as at 15 cycles / sec., and is 5 or 10 times as great at 50 cycles / sec. as with direct current, according to the current density employed. The eddy current loss in stator conductors increases with frequency, and has to be taken into consideration in the design of large generators.

2. *Frequency and Induced E.M.F.*—The general formula for the E.M.F. induced in a coil of T turns by an alternating magnetic flux of maximum value ϕ, and of frequency f, is: $E = kf\phi T$, where k is a numerical factor. Two cases arise: (i) that of a particular winding (*i.e.* T constant) used on or subjected to different frequencies; (ii) that of a winding in which the number of turns is varied so that the maximum flux ϕ is the same at two different frequencies f_1, f_2. It is assumed that, in both cases, the applied or induced E.M.F. E is the same. These assumptions involve the product $f\phi$ being constant in case (i), and the product fT being constant in case (ii).

Case (i) is that of a winding designed for one frequency and operated on another. The consequences are:—

(*a*) Reduced frequency f demands greater flux, ϕ, for the same E.M.F., E. This involves increased magnetising current and lower power factor.

(*b*) The hysteresis loss (§ 34) increases with $\phi^{1.6}$, but this increase is partly compensated by the lower frequency with which the cycle is completed. The eddy current loss (§ 39) varies with $f^2 \phi^2$, and is, therefore, constant in the case considered.

(*c*) The higher magnetising current required to produce the greater flux involves higher copper loss and, therefore, reduced efficiency.

Case (ii) is that of a constant-flux winding, the number of turns in the latter being varied to suit the changed frequency. In this case, T is increased as f decreases, ϕ remaining constant,

but at the lower frequency a higher flux density is permissible for the same hysteresis and eddy current losses, hence the iron circuit may be lighter (§ 41). At 40 or 50 cycles / sec., or higher frequencies, the iron losses often determine the permissible flux density, whereas at 25 cycles and lower frequencies the limit to flux density is that of magnetic saturation (§ 43).

3. *Frequency and Synchronous Speed.*—The relation between the 'synchronous speed' n r.p.m.; the number p of *pairs* of magnetic poles in a generator, motor, etc.; and the supply frequency f cycles / sec., is $n = 60f / p$. This formula gives the actual speed of any synchronous machine (*e.g.* alternator, synchronous motor, rotary converter), but the actual speed of an induction motor is less than the synchronous speed by the amount of the slip which varies with the design of the machine and increases with the load.

The synchronous speeds of machines with from 2 to 12 poles, when operating on supply frequencies of 15, 25, 50, and 60 cycles / sec. are shown in Table 11. These figures show clearly:

TABLE 11.—*Synchronous Speed at Various Frequencies.*

Number of Field Poles.	Synchronous Speed, Revs. per Min., with Supply Frequency.			
	15 Cycles.	25 Cycles.	50 Cycles.	60 Cycles.
2	900	1 500	3 000	3 600
4	450	750	1 500	1 800
6	300	500	1 000	1 200
8	225	375	750	900
10	180	300	600	720
12	150	250	500	600

(i) The fewer number of poles required at lower frequency for given speed (r.p.m.), and hence the advantage of low-frequency supply where motors of very low speed are required. Except in very heavy driving (*e.g.* steel mills) it is cheaper to use high-speed motors with gear reduction; 50-cycle supply is then as convenient as 25-cycle supply. (ii) The greater number of available synchronous speeds where higher frequency is employed, *e.g.* only one intermediate speed between 500 and 1 500 r.p.m. with 25-cycle supply, compared with three speeds when 50-cycle supply is used. This is an important consideration.

4. *Influence of Frequency in Specific Applications.*—The general effects of high and low frequencies, within the range of values used in commercial supply, may be summarised as follows :—

Generators.—The maximum speed for a 15-cycle generator is 900 r.p.m. (Table 11) which is low for driving by steam turbine. At 25-cycles a 2-pole machine must be used for 1 500 r.p.m., whereas a lighter 4-pole machine could be used for 50-cycles and the same speed. The iron losses are lower at lower frequency. The electrical phase angle corresponding to a given mechanical displacement of the rotor is smaller in low-frequency than in high-frequency generators for the same speed; this means that engine-driven generators can be operated in parallel more easily and stably at low than at high frequencies; the distinction does not arise where turbines are used because these have no cyclic irregularity of speed. Large turbo-alternators (say 15 000 kw.) are about 10 % dearer for 25 cycles than for 50 cycles.

Transformers.—The efficiency of a particular transformer is higher at higher frequency for the same E.M.F. (*see* (2) *Case* (*i*) above). On the other hand, in the case of transformers designed for the frequency on which they are operated, the losses are lower at lower frequency; if the maximum flux density is limited by the permissible iron losses the low-frequency transformer is at an advantage, but if special low-loss steel be used the permissible flux density is determined by saturation, and the less weight of steel required in a 50-cycle transformer compared with a 25-cycle transformer more than compensates for the higher losses in the former. Modern 50-cycle transformers are generally 25 to 30 % lighter and about 25 % cheaper than 25-cycle transformers for the same output.

Transmission Lines.—As explained in section (1) above, lower frequency results in lower voltage drop unless the electrostatic capacity of the line is considerable in which case the inductive drop may be reduced, balanced or even overbalanced (§ 318).

Motors.—At given speed a synchronous motor is pulled out of step or caused to 'hunt' more easily if the frequency be higher because the number of poles is then greater (Table 11) and the electrical displacement corresponding to given mechanical displacement is greater.

A given induction motor will generally operate satisfactorily with $\pm$ 10 % variation from the frequency for which it was designed. For given synchronous speed, the number of poles required decreases as the frequency is lowered (Table 11), and the fewer the poles, the higher the power factor (Chapter 28) and the higher the overload capacity. On the other hand, the low-frequency motor is generally larger and more expensive. For equal power factor a low-speed 25-cycle machine is smaller and cheaper than a 50-cycle motor, but as the condenser capacity required to compensate for the wattless component is relatively less at higher frequencies (§ 160 *a*), the 50-cycle machine can compete if it is designed for low P.F. and used in conjunction with a phase advancer; this is practicable only in the case of large motors.

The series-wound single-phase commutator motor is the principal machine benefiting by a supply frequency lower than 25 cycles. The inductance drop in the field and armature windings decreases as the frequency is lowered, and the power factor and efficiency are therefore improved. At the same time, the E.M.F. induced in the coils short-circuited by the brushes is reduced, and commutation is better at lower frequency. Where these motors are used for traction a frequency of 15-cycles / sec. is sometimes employed, but below 25-cycles there is a

risk of slipping at the driving wheels due to variations in the torque which is necessarily zero every half-cycle in a single-phase motor. For the same service 15-cycle motors of this type are lighter than 25-cycle motors and, since greater output can be obtained from a 15-cycle motor of given size, it is often possible to use fewer motors on the train. This more than compensates for the lighter 25-cycle transformers.

Lighting.—Arc lamps operate more steadily and efficiently on 50-cycle than on 25-cycle supply, but filament lamps operate equally well on all frequencies above 25-cycles / sec. At lower frequencies flicker becomes evident particularly if the mass of the filament be small.

Rotary Converters.—For many years the performance of rotary converters was much better at 25 than at 50-cycles / sec., but by improvements in design and construction—notably the use of higher peripheral speeds and the use of commutating poles—rotary converters for 50 or 60 cycles / sec. have been made practically equal in cost and efficiency to those for 25-cycle supply. Where high voltage D.C. is to be used for traction service, low-frequency A.C. primary supply offers some advantage in that single-commutator rotary converters can be built for 3 500 V D.C. when the A.C. supply is at 15 cycles, 2 000 V when the supply is at 25-cycles, and only 1 000 V when the supply is at 50-cycles.

Frequency Changers.—These machines may be used to raise or lower the supply frequency to suit the special requirements of a particular load, but generally they are used as a link between interconnected distribution systems of different supply frequencies. The ratio of the number of poles on the two sides of the machine must equal the ratio of the two frequencies; the 2 : 1 ratio between 50- and 25-cycle systems makes possible a much cheaper frequency changer than the 24 : 10 pole combination required between 60- and 25-cycle systems.

(5) *Standardisation of Frequency.*—For twenty-five years or longer the balance of favour has oscillated between 25-cycles on the one hand and 50 or 60-cycles on the other. In the present state of electrical practice there is no radical difference between the costs and efficiencies of apparatus designed for 60- and 25-cycle supply so far as general power and lighting services are concerned. The technical distinctions between 60- and 50-cycle supplies are practically negligible. There is no likelihood of a frequency higher than 60-cycles / sec. being employed in any new supply system. In America both 60- and 25-cycle supplies are used very extensively, but the higher frequency is likely to predominate. In this country the Electricity Commissioners have decided upon a policy of eliminating all odd frequencies (of which there are at present many), ultimately reducing the main frequencies in use to 50- (standard), 40- and 25-cycles / sec. Apart from the advantages of unification in reducing the capital expenditure on turbo-alternators, transformers, motors, etc., and the simplification and economy in manufacture due to the employment of fewer types of plant and apparatus, the adoption of a common frequency would

remove engineering difficulties in the interchange of energy between different undertakers and the ultimate linking-up of districts. Financial considerations, however, make it impracticable to alter the frequency in existing installations by any process of substitution. All that can be hoped for is ultimate restriction to the frequencies (50, 40, and 25 cycles) now used in the principal supply systems of the country.

136. British Standard Rating for Electrical Machinery.—The International Electrotechnical Commission's Rules for Electrical Machines (I.E.C. Publication 34) and the B.E.S.A. Report No. 72 attempted to eliminate the somewhat contradictory term 'overload capacity' from the rating of motors, generators, and transformers. In the third edition of this book, however, the opinion was expressed (p. 254) that it would be long before the term 'overload' was finally abandoned. Since then it has been found commercially expedient to restore 'overload capacity' as part of the standard rating of electrical machinery. This is done for industrial electric motors and generators with Class A insulation * by B.E.S.A. Report No. 168, which replaces Report No. 72 in so far as it applies. Other B.E.S.A. Reports will doubtless modify the standard rating of other machinery covered by Report No. 72 in the same sense, and the I.E.C. (at the time of writing) has under consideration the adoption of an additional international rating for industrial machines, providing for a lower temperature rise and associated with a capacity for a sustained overload.† Thus, whilst there is a good *prima facie* case for basing the rating of a machine (motor, generator, transformer, etc.) upon the output which *includes* the 'sustained overload capacity,' it may be assumed that the established industrial practice of distinguishing between the 'rated' output and the 'overload capacity' of machines will receive official recognition.

The B.E.S.A. reports should be studied in the original (the cost of the publications being nominal) for full particulars as to the British Standard Ratings, but the following (*unofficial*) summary of the rating clauses in Report No. 168 will serve for general information :—

* Cotton, silk, paper, and similar materials when impregnated or immersed in oil, also enamelled wire.

† After much discussion, agreement was reached at the Geneva (1922) meeting of the I.E.C.; but the decisions arrived at, and reported in the technical Press, require confirmation at a plenary meeting.

This specification applies to industrial motors and generators of 1 B.H.P., kW or kVA and upwards per 1 000 r.p.m. wound for pressures not exceeding 7 000 V; and does not apply to turbo-type machines, rotary converters, and traction motors. Overload requirements for single-phase motors are not yet included.

In no case may the maximum temperature of windings (with Class A insulation) or of cores with which they are in contact exceed 90° C. The sustained overload specified below is permissible only if the temperature of the cooling air does not exceed 30° C. (86° F.); if the cooling air exceeds 30° C. *either* the sustained overload must be reduced in magnitude or duration *or* the continuous load must be reduced below the rated load.

The *British standard continuous rating* defines the load which can be carried for an unlimited period without exceeding the limits of temperature rise given in Table 12. The *British standard short time rating* defines the load which can be carried for a specified time (either 1 hr. or ½ hr.) without exceeding the limits of temperature rise specified in Table 12; the test being started with the machine cold. In both cases the conditions of the test must be those of the rating and of B.E.S.A. Specification No. 168 (*q.v.*).

A generator rated for two limits of voltage must have its rated current and output determined at the higher voltage. A change-speed motor shall have a definite rating for each speed, and a variable-speed motor for each of its limiting speeds.

TABLE 12.—*Temperature Limits for Industrial Motors and Generators (Class A Insulation).*

Part.	Temperature Rise * (by Thermometer). Machines (other than Totally Enclosed) with Continuous Rating.	Temperature Rise * (by Thermometer). Machines with Short Time Rating, and Totally Enclosed Machines.
	° C.	° C.
Windings and cores with which they are in contact . . .	40	50
Commutators	45	55
Slip rings—open type . . .	45	55
,, ,, —enclosed type . .	55	55
Uninsulated parts, and cores not in contact with insulated windings	Such that there is no risk of injuring insulation on adjacent parts.	

Motors and generators (other than single-phase motors) shall be capable of sustaining without injury the overloads specified below † after having attained the temperature rise corresponding to continuous operation at rated load. Rated voltage and frequency must be maintained.

* In the case of machines to be used at altitudes of 3 300 ft. or more (up to 10 000 ft.) above sea level, the permissible temperature rise is reduced 1½ °/₀ for each 1 000 ft. above sea level. Machines for service above 10 000 ft. are not considered standard.

† The summary here given is arranged for easy comparison of the general requirements; the specification should be consulted where actual tests are concerned.

	Limits of Output *Per* 1 000 *R.P.M.*	Sustained Overload.		Momentary Overload.	
		Machine not Totally Enclosed.	Machine Totally Enclosed.	Machine not Totally Enclosed.	Machine Totally Enclosed.
MOTORS (overload refers to *torque*).					
(*a*) *Continuous rating*	Less than 4 and down to 1 B.H.P.	25 %; ¼ hr.	nil	—	—
	4 B.H.P. and over D.C. up to 150 B.H.P. incl.; all sizes A.C.	25 %; 2 hrs.	nil	—	—
		—	—	100 %; 15 secs.	75 %; 15 secs.
	All sizes	—	—	50 %; 1 min.	50 %; 15 secs.
(*b*) *Short time rating*	All sizes	nil	nil	100 %; 30 secs.	100 %; 30 secs.
GENERATORS (overload refers to *current*).					
Continuous rating .	Less than 3 and down to 1 kW or kVA	25 %; ¼ hr.	nil	—	—
	3 kW or kVA and over	25 %; 2 hrs.	nil	—	—
	All sizes	—		50 %; 1 min.	50 %; 15 secs.

The methods for stating output are: (i) *D.C. Generators*—Output in kW available at the terminals (ii) *Alternators*—Apparent output in kVA available at the terminals. Unless otherwise specified, the P.F. of the generator is taken to be 0·8. (iii) *Motors*—Mechanical output in H.P. and kW available at the shaft. (iv) *Transformers*—Apparent output in kVA available at the secondary terminals.

As the average output of an alternator is generally about 80 % of the rated output, the efficiencies of the machine and of the prime mover which drives it should be highest at this output. The prime mover should, however, be capable of driving the generator at 40 or 50 % above the most economical output (12-20 % above rated output), so as to allow for emergent short-period overloads. This is often overlooked in the case of internal combustion engines and water turbines.

137. Homopolar or Acyclic Dynamos.—These machines, which are sometimes (erroneously) called unipolar dynamos, are

based on the fact that if a copper disc be rotated between the poles of a horseshoe magnet (about an axis joining the poles, the flux being perpendicular to the disc) a constant E.M.F. is induced between the rim and the spindle of the disc. It was in this form that Faraday discovered the dynamo. Similarly, if a hollow metal cylinder be rotated in the annular air gap between an internal N (or S) pole and an external S (or N) pole, a constant E.M.F. is induced between the ends of the rotating cylinder. Replacing the solid disc or cylinder by armature bars connected in series we have the two types of homopolar dynamo, *viz.* the disc or radial type, and the cylindrical or axial type. The armature conductors always cut the magnetic flux in the same direction, and this is the only type of D.C. generator in which direct current is actually induced in the armature conductor (§ 132). It is therefore unnecessary to use a commutator, and for this reason many attempts have been made to develop the homopolar machine as a competitor of the commutator-type D.C. generator. A number of armature conductors are connected in series and current is collected by brushes bearing on slip rings.

Unfortunately it is not economical (if possible) to build homopolar machines of useful capacity for the voltages employed in general D.C. distribution. Also, the electrical difficulties of design are increased at turbine speeds, for which the elimination of the commutator is, in itself, most desirable. A homopolar dynamo rated at 2 000 kW, 260 V, 7 700 A, 1 200 r.p.m. was built some years ago * but serious difficulties were experienced in construction and operation, and the experiment does not appear to have been repeated. The homopolar dynamo is essentially a low voltage, heavy-current machine, but even in electro-chemical work where currents of many thousand amperes are sometimes required at a pressure of a few volts, it is generally more satisfactory to employ a motor generator driven from the ordinary supply mains.

138. Shunt, Series, and Compound-Wound D.C. Dynamos.—The general design of the armature and field magnets remaining the same, the electrical characteristics of D.C. dynamos are very different according as the field coils are shunted across the armature (Fig. 30), connected in series with the armature (Fig. 31), or connected partly in shunt and partly in series with the armature

---

* *See Engineering*, July 19, 1912, p. 92.

(Fig. 32). In these three cases the machine is said to be shunt, series, or compound wound respectively.

There may be any even number of magnetic poles from two upwards; but, whereas the applied pressure of the supply ensures the energising of the magnet coils on a motor, a generator has to excite its own magnets. It occasionally happens that the iron of the magnet is free from any vestige of residual magnetism; but under ordinary circumstances it retains a sufficient amount of magnetism to start the cycle of operations known as 'building up the field.' The armature is being driven by its prime mover in the weak field of the iron alone, and this residual magnetism is sufficient to cause a small E.M.F. in the armature coils; this in turn sends a small current through the magnetising coils and so strengthens the field, and thus by imperceptible increments the field is built up rapidly to full strength.

Shunt Dynamos.—Where batteries are used shunt-wound generators are essential, as the other types would reverse their direction of rotation if accidentally driven as motors; this would happen if the generator voltage dropped below the battery voltage. The voltage when cells are being charged must be much higher than the pressure of supply to the lamps (Chapter 18) and the necessary regulation is obtained by varying the strength of the shunt current. Shunt-wound generators can also be used in any case where constant pressure is required in the external circuit; by varying the current in the field circuit, by means of a 'shunt resistance' or 'rheostat' placed in series with the magnet winding, the voltage in the external circuit can either be maintained or varied at will, so as to compensate for the loss of pressure in the mains and give constant pressure at a distant point. If the brushes of a shunt machine are put down, thus closing the circuit of the magnetising coils, and the machine is then run up to speed with the external circuit open, the field will be built up to full strength; the pressure across the brushes will be at its full value, and the shunt current will be volts ÷ shunt resistance, both of which are practically constant while the speed remains so. Allowance can be made for such variations as occur (Chapter 40, *Dynamos*). If the external circuit is now closed the load can be increased from no load to full load. As the amperes increase there is a drop of pressure in the armature, due to its resistance, and the brush volts fall below the armature volts.

Consequently the field is weakened. This is shown in the 'characteristic curve' of a shunt machine (Fig. 30), which can be constructed from the readings of volts, amperes, and speed taken on test at various loads, after correction as explained in Chapter 40. The curve shown is called the 'external characteristic;' if the armature resistance is measured, and the value of the lost volts in it (*IR* in the diagram) is calculated from the amperes at

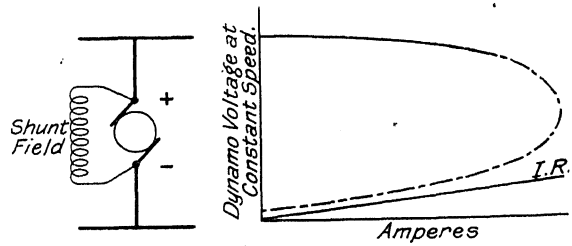


FIG. 30.—Connections and characteristic curve of shunt dynamo.

different points, then the 'internal characteristic' of the machine can be plotted by adding these lost volts to the previous curve at each reading. The full curve represents the working range of the machine, and the dotted part shows what would occur with sufficient overload.

Series-wound Dynamos.—Series-wound generators are only used where a constant current of so many amperes is required in

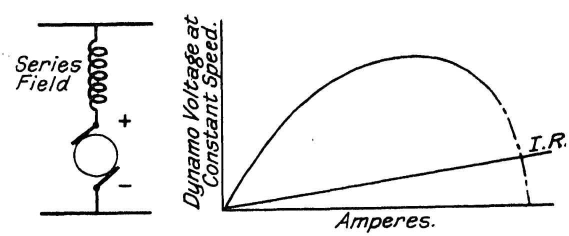


FIG. 31.—Connections and characteristic curve of series dynamo.

the external circuit, as in the case of series arc or incandescent street lighting (Chapter 25); the pressure is then varied according to the number of lamps in use. The external characteristic curve of a series dynamo is shown in Fig. 31. In these machines the field circuit is only closed when the external circuit is closed, so that the load comes on; and the current in the field coils is not constant, but varies directly with the load in amperes. It will be

noticed that beyond the bend of the curve the current is almost constant, regardless of the pressure, and an arc lighting machine utilises this part of the curve. To obtain the internal characteristic in this case the drop in pressure *IR* due to the resistance of the armature and the field coils in series must be calculated and added at each reading.

Compound-wound Dynamos.—For installations not using batteries the compound-wound generator is usually employed, owing to its automatic regulation; and also for D.C. tramway systems, except those supplied from converters. The shunt coils give a constant excitation, but the additional ampere-turns of the series coils vary according to the current in the external circuit, which is flowing round them; consequently, as the current rises and the loss of pressure in the circuit increases, the additional strength of the field magnets automatically raises the pressure of generation

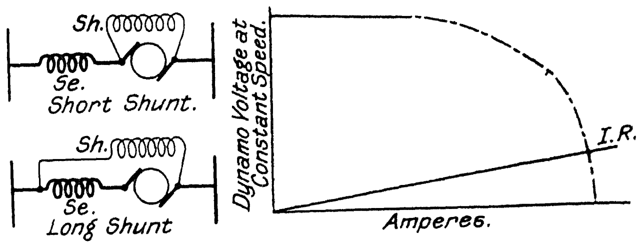


FIG. 32.—Connections and characteristic curve of compound dynamo.

to a corresponding degree, so that the resulting pressure at the far end of the line remains constant. An examination of the two preceding figures makes this clear, the drop of pressure in the former being compensated by the rise in pressure of the latter. The resulting external characteristic of a compound dynamo is shown in Fig. 32, and in a well-designed machine is almost a straight line over the working range. The line may be either level (level compounding) or rising (over-compounding), so that the drop of pressure in feeders as well as in the machine itself may be compensated; in this case the ampere-turns on the series coils are designed to raise the pressure in a higher ratio than the current increases; this is especially the case in electric tramway stations.

139. Interpoles.—Owing to the reaction of the armature flux on that of the field magnets there is always some distortion of the

magnetic field in which the armature rotates, and hence in the position of the 'neutral zone' (of zero field) in which commutation can be effected sparklessly. This distortion is particularly noticeable at heavy loads or when the main field is weakened very considerably in the course of obtaining wide voltage regulation or speed regulation over a wide range (Chapter 29), in the case of a motor. In order to prevent sparking, the angle of lead of the brushes may be altered by moving the latter forward, in the direction of rotation in the case of a generator, and backwards in the case of a motor, as the load increases. To obviate this adjustment, small commutating poles or 'interpoles' are placed alternately with the main poles and excited by a few turns of wire in *series* with the load. A suitable commutating field is thus maintained automatically beneath the interpoles at all loads. The polarity of each interpole must be the same as of that main pole towards which the brush would otherwise have to be moved. Clearly, the polarity of interpoles with regard to the main poles is opposite in motors to what it is in generators, but by connecting the interpole windings in series with the armature the correct polarity is produced automatically for either motor or generator action. In practice a shunt having inductance is connected across the terminals of the interpole winding and adjusted for sparkless commutation.

140. **Generator Excitation.**—Permanent magnets are used to provide the magnetic flux in small magneto generators, such as those used for ignition purposes in automobiles, etc., for some electro-medical work, and for the measurement of speed of revolution (§ 123). All generators for lighting and power supply are, however, 'excited' by direct current passed through solenoids wound round cores which constitute the magnetic poles of the field system (§§ 40 *et seq.*, 133). Direct-current generators are generally 'self-excited' by part of the current produced in the armature, the several methods of connecting the field circuit and the resultant characteristics of the machine being as described in § 138. There is no reason, save that of convenience, why every D.C. generator should not be 'separately excited' from a suitable independent supply; this is only done, however, in the case of certain types of boosters (§ 142) and in some methods of motor control (Chapter 29) when it is desired to vary, over a wide range, the E.M.F. developed by a generator running at constant

speed. All D.C. generators for ordinary supply purposes are self-excited.

Alternators deliver only alternating current, and the direct current for their field circuits must be provided from an independent source. Generally, a small shunt-wound D.C. generator is mounted on an extension of the alternator shaft; this generator —commonly called the 'exciter'—delivers current at from 100-250 V to the alternator field circuit. The exciter is either self-excited or separately excited. By varying the resistance in the field circuit of the exciter, the voltage applied to the alternator field circuit, and hence the A.C. voltage generated by the alternator, can be controlled (§ 147). To allow for the possibility of breakdown in the exciter or its circuits, it is usual to arrange that the alternator can be excited from an alternative source of direct current, such as a steam-driven D.C. generator, a rotary converter, a motor generator, or a battery of secondary cells. In water-power plants it is not unusual to mount the exciter between a turbine and an induction motor, so that it can be driven either independently or from the bus bars of the supply. In some stations all the alternators are excited from a common set of bus bars, instead of by individual exciters on each main machine; it is then necessary to provide two independent sources of supply for the D.C. bus bars, one source being held in reserve. In any case provision must be made for separate adjustment of the field strength of each alternator for voltage control.

The power required to excite an alternator rises rapidly as the power factor of the A.C. system decreases (§ 155). Under average conditions the kW capacity of the exciter is from 0·5 to 1·0 % of the kW capacity of high-speed generators (from 10 000 to 1 000 kW respectively) and about twice as great in the case of low-speed generators.

141. Balancers and Three-wire Generators.—In order to combine the advantages of higher voltage for transmission and for the supply of power loads with lower voltage for the supply of incandescent lighting and other domestic circuits, direct-current systems are generally operated on the 'three-wire system.' The energy consumed is fed to the 'outer' conductors at, say, 440 V or 500 V. All but the smallest motors are connected 'across the outers,' but lighting and small power devices are designed for 220 or 250 V (*i.e.* half the voltage between the outers) and

arranged in two groups of as nearly as possible equal current consumption, these two groups being connected in series between the outers. As the two groups are distributed in many premises it is necessary to use a neutral conductor to act as a bus bar for the series connection of the two groups and, as it is impossible to maintain exactly equal current consumption in each group, it is necessary to provide some means of dealing with the out-of-balance current, otherwise the voltage division between the two groups would be unequal (*cf.* § 95, volt box).

The simplest method of supplying a 3-wire system is to use two generators connected in series between the outers, the common terminal of the two generators being connected to the neutral conductor. This arrangement is used in many of the older stations. The two generators may be driven by one engine, and if the load is not balanced accurately between the two sides of the system one generator is loaded more heavily than the other. This system demands constant attention in changing feeders from one side of the system to the other so as to equalise the load, and in regulating the generator fields to maintain equal voltage, notwithstanding some lack of balance in the division of the load. A less costly equipment, and one which needs less attention in service, consists of a single main generator designed for the voltage between the outers, and a motor-generator set the machines of which are coupled mechanically and connected electrically in series across the outers, with their common terminal connected to the neutral (Fig. 33). The operation of such an installation is explained fully in Chapter 20. So long as the load is balanced between the two sides of the 3-wire system the two machines of the 'balancer' set run as motors in series across the outers. If, however, the load be unbalanced the machine which is connected across the more heavily loaded side runs as a generator (driven by the other machine) and supplies the out-of-balance current. The action of the balancer machines as motor or generator is determined by the division of voltage between the two sides of the system, and there are many possible arrangements for the field circuits of the balancers. The balancers

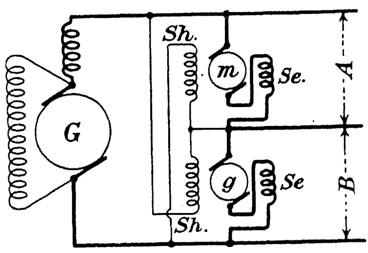


FIG. 33.—Motor-generator balancer for 3-wire system.

shown in Fig. 33 are compound-wound (§ 138), the shunt field for each machine being connected across the other half of the system and the series coils assisting the shunt coils. If the load be heavier on the side B of the system, the speed of the machine m rises (due to the increased voltage across A and the reduced field strength) and this machine drives g as a generator, the field of the latter being simultaneously strengthened. Both current and voltage balance are thus maintained within close limits.

An alternative method of balancing is to use two batteries of storage cells (either alone or in conjunction with a booster, § 142) instead of the machines m, g (Fig. 33).

Another method is illustrated by Fig. 34 in which A represents the armature winding of a D.C. generator (supposed two-pole for simplicity) connected to the outers of a 3-wire system. Diametrically opposite points B,C on the armature winding are connected

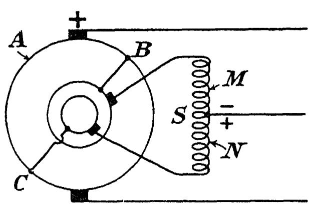


Fig. 34.—Single-phase static balancer for 3-wire system.

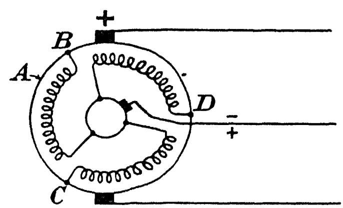


Fig. 35.—Auxiliary armature-winding used for balancing 3-wire system.

to slip rings, the brushes on which are connected to a static balancer S. The latter is a choking coil (§ 45) of such impedance that only a small alternating current flows through it from the armature. The neutral wire of the system is connected to the centre point of S and out-of-balance current flows equally in both directions from this point to the armature, encountering only the ohmic resistance of S, which is low. Better results are obtained by connecting the neutral to the common terminal of three choking coils connected in 'star' (§ 143) to three equidistant points on the armature winding. Similarly, if a rotary converter is used to supply a 3-wire system, the neutral line is connected (either directly or through a regulating booster) to the neutral point of the low voltage side of the transformer feeding the converter.

Fig. 35 represents the use of a main armature winding A to feed the outers of a 3-wire system, and an auxiliary winding connected between three equidistant points B,C,D on the main

winding and a slip ring connected to the neutral. The auxiliary winding is in the same slots as the main winding, but has only half as many turns. Exact voltage balance is maintained; the auxiliary winding deals with out-of-balance current and adds to the output of the machine even when the load is balanced.

Instead of connecting the neutral directly to the centre point of S (Fig. 34), tappings may be taken from points MN, at equal distance from the centre, to a revolving commutator which rectifies the tapped current and applies it to the more heavily loaded side of the system.*

142. **Boosters.**—A direct-current booster consists simply of a motor-generator designed and connected in one of many alternative ways according to the purpose which it is to serve. For example, to compensate for pressure-drop in a feeder, the motor of a boosting motor-generator set may be connected across the mains whilst the generator armature, in series with the positive conductor, carries the full current flowing in the latter, and adds a few per cent. to the E.M.F. operating in the feeder circuit, without affecting the pressure in other circuits supplied from the same bus bars. The amount of 'boost' may be regulated by hand control of the generator field, or by such connection of the fields that the motor speed or the generator field (or both) increase with increasing load on the feeder.

An alternative method of regulating the voltage delivered by a feeder consists in 'floating' a storage battery across the *far end* of the feeder. The cells are charged through the cable during light-load periods; but on heavy loads the supply volts at the end of the cable tend to fall below the battery volts, hence the cells discharge and limit the current taken through the cable. So long as the charge or discharge of the cells is determined solely by the voltage at the far end of the feeder, the voltage variation is bound to be considerable; actually it is about $2{\cdot}2 - 1{\cdot}9 = 0{\cdot}3$ V total variation, or $0{\cdot}15$ V up and down from normal, per cell in the battery (*e.g.* $\pm\ 37{\cdot}5$ V variation in the case of a 250-cell, 500 V battery). If, however, the charge or discharge of the cells be determined by a booster, the voltage variations at the far end of the feeder are much reduced. The booster armature is in series with the battery and adds its E.M.F. to the feeder voltage, so that the

* 'Regulating the Voltages of a 3-wire D.C. System Equalised by Static Balancers,' R. D. Archibald. *Jour. I.E.E.*, Vol. 60, p. 303.

battery is charged when the load on the feeder is light; when the load increases, the booster E.M.F. is reversed, *i.e.* added to the battery E.M.F., so that the cells discharge and relieve the feeder of some of the total load. The requisite variations in the E.M.F. of boosters used for battery regulation are generally provided by differential excitation of the field system. Thus a shunt winding separately excited by the feeder voltage may tend to cause the booster to charge the battery, whilst a series winding, carrying all or part of the load current, may tend to make the booster discharge the battery. In other systems an exciter (§ 140), on the same shaft as the booster motor-generator, is regulated automatically to produce that direction and strength of excitation in the booster which gives the desired boost.

Whereas a floating battery without booster can only be used with shunt-wound generators, the drooping characteristic of which (Fig. 30, § 138) permits the battery to discharge as the feeder load increases, a battery with booster regulation can be used in conjunction with a main generator which is compounded or over-compounded to compensate for pressure drop in the feeder. The field cores of booster dynamos are laminated in order that the flux may be varied rapidly and without serious eddy current loss.

The use of boosters to augment the generator voltage when charging batteries, and to supplement the battery voltage when the cells approach discharge is explained in Chapter 18. 'Negative' boosters are used to reduce the pressure drop in the return feeders of a tramway and thus prevent large return currents straying from the rails (Chapter 35).

In A.C. circuits 'boosting' may be effected in exactly similar manner, using static transformers instead of rotary machines. The transformer primary is connected across, and the secondary in series with, the circuit to be boosted; and variable-ratio tappings provide for voltage regulation. If the auxiliary transformer be used to oppose the main pressure it is called a 'bucking' transformer. Where continuous gradation of boost or buck is needed, an 'induction regulator' may be used. This consists of a static transformer, the primary of which is wound on a stator and the secondary on a rotor; there is a very small air gap between the stator and rotor (no more than mechanical clearance), and the windings are arranged so that the E.M.F. induced in the secondary can be varied by changing the setting of the rotor, by hand or

servo-motor. The regulator is static in action, the rotor being moved through a fraction of a revolution to change the boost or buck. The presence of the air gap makes the magnetic leakage and exciting current of an induction regulator high compared with those of an ordinary transformer.

The use of synchronous A.C. boosters in the pressure regulation of rotary converters is mentioned in Chapter 17.

Whether boosting statically or by rotating machinery, the booster must be capable of carrying the full load current so that if the pressure is to be boosted (or bucked) by n %, the kVA capacity of a booster dynamo or the secondary of a boosting transformer must be n % that of the load supplied. On the other hand, the capacity of the motor driving a booster dynamo, or of the primary of a booster transformer, need only equal the maximum kVA of boost (plus an allowance for losses in the booster set). This distinction is important in the case of a booster used for battery regulation; the motor capacity may be considerably less than that of the booster dynamo because the latter must be capable of supplying the maximum voltage of boost and of carrying the maximum current; these maxima do not occur simultaneously, and it is the maximum actual output which determines the size of the driving motor.

143. Synchronous Alternators: Mesh and Star Connection.—The synchronous alternator is the type almost invariably used for the production of alternating current (see, however, § 144), and throughout this book the term 'alternator' is—in accordance with usual practice—taken to mean a synchronous machine unless otherwise specified. This machine (which is reversible and can also be run as a synchronous motor) consists of a field-magnet system, energised by a separate D.C. exciter dynamo, and a system of coils in which A.C. is generated. As explained in § 132, there is no essential difference between a D.C. dynamo and an alternator. Single-phase A.C. is produced in the armature winding of a D.C. dynamo, and if we use slip rings instead of a commutator we make this single-phase current available in the external circuit. By mounting three single coils of wire on the armature, the angles between the coils being 120°, we obtain three distinct single-phase currents differing 120° in phase (*see* Fig. 5, § 15). We might collect these three currents separately by a pair of slip rings for each phase, but it is usual to connect the three phases: (i) in

series to form a 'mesh' or 'delta' winding, from the apices of which supply is taken (Fig. 36); *or* (ii) in 'star' or 'Y' connection, in which case one end of each phase is connected to a common neutral point, and supply is taken from the three remaining terminals (Fig. 37). (*See also* Chapter 20.) In either case only three slip rings are required. There is no essential difference between a single-phase and a 3-phase alternator except for the provision of the additional coils for the second and third phases.

With mesh connection (Fig. 36) the voltage E between lines equals the phase voltage e of the generator, but each line is connected to two separate phases and the line current $I = \sqrt{3}$ times the phase current i. The power per phase $= ei \cos\theta$ (§ 55) $= (EI \cos\theta)/\sqrt{3}$; and the total power $= 3 \times$ power per phase $= \sqrt{3}\,EI\cos\theta$. With star connection (Fig. 37), the line current I equals the phase current i, but the voltage between lines equals

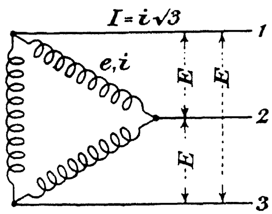


FIG. 36.—Mesh or delta connection.

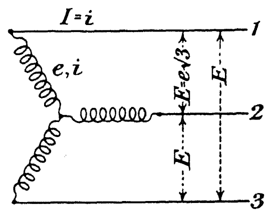


FIG. 37.—Star or Y connection.

$\sqrt{3}$ times the phase voltage; the total power $= 3\,ei\cos\theta = 3(E/\sqrt{3})\,I\cos\theta = \sqrt{3}\,EI\cos\theta$, as before. For given phase voltage and current, the mesh connection requires line conductors of larger cross-section, and the star connection requires more insulation between lines. (*See also* § 314.)

The standard pressure and frequency of generation are discussed in § 134; and voltage regulation in § 147.

144. Asynchronous or Induction Alternators.—The asynchronous or induction generator consists essentially of an A.C. induction motor with a phase-wound rotor (Chapter 28), the latter being driven mechanically at higher than the synchronous speed (§ 135 (3)). There is no special field winding and no D.C. excitation in a generator of this type. The machine can only be used in conjunction with synchronous generators (§ 143), the latter magnetising the asynchronous generator and also 'setting' the frequency at which the induction machine operates. As long as

the rotor of the induction machine is running below synchronous speed the machine is simply an induction motor (whether or not it is coupled to a prime mover); but directly the prime mover drives the rotor above the synchronous speed corresponding to the frequency of the *synchronous* generators and the number of poles in the induction machine, the rotor absorbs power from the prime mover, and current induced in the stator windings by the rotating polyphase field of the rotor is delivered to the network, thus supplementing the output of the synchronous generators. Under all conditions, however, the synchronous generators supply the magnetising current of the induction generator, hence the use of the latter reduces the power factor of the system. Notwithstanding this serious disadvantage, induction generators offer a convenient means of adding, to an existing A.C. system, power derived from a windmill (§ 165) or small water turbine. An induction generator does not require to be synchronised (§ 149) and can therefore be started and switched into circuit by simple automatic gear whenever there is wind or water power available (§ 187). The main advantage, however, of the induction generator in the utilisation of variable natural power, lies in the fact that the rotor speed bears no definite relation to the frequency of the current produced. The speed of an induction motor can be varied over a considerable range by varying the resistance of the rotor circuit (Chapters 28, 29); similarly, the rotor speed of an induction generator can be adapted to the requirements of a windmill or variable-head water turbine over a considerable range of wind or water conditions by varying the resistance of the rotor circuit. The frequency remains constant at the value set by the synchronous generators on the system. For satisfactory operation of the whole, the kVA capacity of the induction generators should not exceed one-eighth that of the synchronous generators.

145. Mechanical Features of Turbine-Driven Alternators.— Small and medium-sized alternators may be driven by any convenient prime mover (Chapter 6), but the standard machine in all large stations is now the 3-phase alternator driven by steam or water turbine. The mechanical design of steam-driven turbo-generators is influenced primarily and to a very marked degree by the high speed at which the steam turbine must be run to secure highest efficiency. It is possible to use geared turbines, and this arrangement is sometimes applied to the driving of D.C. generators,

which can hardly be built to operate well at efficient turbine speeds. A better solution, however, is to use 3-phase alternators for all supply purposes in turbo-driven stations, then producing such D.C. as may be required by use of rotary converters or mercury vapour rectifiers (Chapter 17). The non-salient pole type of alternator is practically standard construction for turbine driving. It is compact, economical, and can be built in any required size. The design and construction of turbo-alternators are matters outside the scope of this book, but the following notes give a useful indication of the difficulties encountered and the general means by which they are overcome.

In early days the limitation of speed imposed by generator design checked the development of the turbine, but during recent years both turbine and generator have been so developed that speeds of the combined sets have reached the limits corresponding to 2-pole and 4-pole design. The output per machine has been raised, many sets now yielding up to 6 250 kVa at 3 600 r.p.m.; 20 000 kVa at 1 800 r.p.m.; and yet higher ratings at 1 500 r.p.m. (60, 50, and 25 cycles). By way of example, consider a 20 000 kVa, 13 200 V, 3-phase, 60 cycles, 4-pole turbo-alternator. The design of such a machine represents a compromise between stringent mechanical and electrical requirements. The rotor (51 × 75 ins.) weighs about 27 tons and, at 1 800 r.p.m., attains a peripheral speed of about 24 000 ft. per min.; it is cut into irregularly from the periphery, and carries much metal which is not self-supporting. The centrifugal force acting on a mass of 1 lb. at the periphery is about 1 ton. During running, considerable radial stress exists right into the centre, and were the central material removed by boring, material near the bore would be stressed tangentially to about 9 tons per sq. in. at normal speed. To eliminate the difficulty of securing the necessary reliability in very large forgings, and to ensure that none but intentional internal stresses exist in the rotor core, the latter may be built up from relatively thick rolled steel plates, machined on both sides and slightly rabbeted into one another. Such steel costs about 0·8d. to 1d. per lb., and is a good deal cheaper than alternative material of suitable strength. The plates are held together and to the flanged shaft at each end by chrome-nickel steel bolts, tightened to such an extent that the rotor has practically the solidity of a single piece.

This plate construction obviously facilitates the problem of providing radial ventilating slots which, in conjunction with an axial passage beneath the windings, give a good distribution of air for ventilation. The pressure of the rotor coils on their wedges (in this case) exceeds 200 tons per slot when running at 20 % over speed. Special shop equipment is needed to press the windings into their slots, and a three-part retaining wedge (consisting of a central, inverted wedge of bronze and side strips of steel) has mechanical and magnetic advantages. The free copper in that part of the rotor windings external to the core may be supported by a weldless chrome-nickel steel ring designed to carry its own load (about 7½ tons / sq. in. at normal speed), and that of the copper beneath, without radial support from the rotor. Steel is used for the retaining rings, in spite of the electrical and magnetic difficulties it introduces, because mechanical considerations must here take precedence. A comparatively thin sheet of drawn copper outside the ring carries sufficient current to protect the magnetic material below from stray flux.

Circumferential bracing of the rotor winding outside the slots is provided by built-up steel driving horns bolted to the shaft, and by blocking intermediate coils from each other.

It is sound practice to build such a machine as this so that it will withstand dead short circuiting at its terminals when running excited and giving full voltage. Naturally, this ability should not be made an excuse to slacken precautions taken to avoid short circuits. A certain amount of external reactance has its use in some cases in limiting current flow on short circuit; and poor inherent voltage regulation and comparatively low ratio between full-pressure, no-load excitation and full-current, short-circuit excitation are desirable. Enormous forces are exerted upon the windings of the machine when short circuit occurs; the support given to the projecting rotor winding to protect it against centrifugal force may be made to cover also short-circuit stresses; the stator winding may be braced by cast-bronze herring-bone bars placed between the two layers of the end connections, the casting having fins projecting between the two coils on each side of it, so as to reproduce practically slot conditions.

To keep down eddy-current losses in the heavy stator conductors, the latter may be composed of a series of insulated strip-strands, transposed from slot to slot, and connected together only at the beginning and end of the coil to which they belong. As a precautionary measure, the stator insulation should be as nearly fireproof as possible. Various improvements have been effected in the use of mica in this connection, and it is possible that such materials as fused silica may yet come into use for insulation purposes on large generators. So long as the insulation held out there would be no reason to be alarmed at very high local temperatures in such a machine. (A. B. Field, *Jour. I.E.E.*, 54, pp. 65 *et seq.*, abridged).

See also 'Problems in High Speed Alternators and Their Solution,' J. Rosen. *Jour. I.E.E.*, Vol. 61, p. 439.

Steam-driven turbo-alternators have been built for outputs up to 60 000 kW (§ 173), but units of 20 000 to 40 000 kW are generally considered to be more convenient and to give higher overall efficiency in working. Failures of (steam) turbo-generators and suggestions for improvements are discussed in a paper by J. Shepherd, *Jour. I.E.E.*, Vol. 58, p. 125.

The normal speed of water-wheel alternators is relatively low, but the rotor diameter is correspondingly large, and it is necessary that the rotor should safely withstand the 'runaway' speed of the turbine (possibly twice the normal speed). The vertical shaft generators in the Queenston hydro-electric station (Ontario) are rated at 45 000 kVA (each), 3 phase, 12 000 V, 25 cycles, 187 r.p.m., and are coupled directly to 55 000 h.p. water turbines. The height of the generator to the top of the exciter is 35 ft.; the diameter of the generator casing is 24½ ft.; and the main 69 in. thrust bearing is designed for a load of 450 tons including the weight of the rotor and the water thrust on the

turbine. (For further details *see El. World*, Vol. 77, p. 697, and *El. Rev.*, Vol. 91, p. 105.)

146. Efficiency and Ventilation of Generators. — The efficiency of very small generators, up to 10 kW capacity, is usually between 85 and 90 %; that of large generators, from 1 000 to 10 000 kVA or higher, is usually between 94 and 96 %. The value of the efficiency and the load at which it is a maximum can be varied by the designer. Increasing the weight of copper in the machine (relative to the weight of iron) increases the load at which maximum efficiency is reached; whereas increasing the relative weight of iron causes maximum efficiency to be reached at lower load. The best value for the efficiency of a large generator within the range 94 to 96 % is determined by the cost of the higher efficiency compared with the value of the increased output (§ 193).

Engine-driven generators are generally of open construction and, being relatively low-speed machines, they are of relatively large dimensions. There is consequently no difficulty in dissipating the losses without excessive temperature rise. In large turbine-driven generators, however, ventilation constitutes a very serious problem, owing to the increased power and decreased size (per kW) of individual machines. The total losses in a 10 000 kW alternator may be, say, 5 % on full load. Expressed as a percentage, the loss is very small, but in point of fact it represents about 500 kW expended as heat (say 17 therms per hour) in a close-built mass of metal and insulation, the overall volume of which is about equal to that of a large living-room. Natural ventilation by ducts in the cores and openings in the frames is no longer sufficient. A network of air-passages must be provided, and through these huge quantities of air* must be driven either by a blower forming an integral part of the machine or by a central blower delivering air through ducts to a number of machines. The latter arrangement is obviously the more efficient, and it permits air to be drawn conveniently from some point outside the power house and thoroughly cleansed before admission to the generator. Fouling of air-ways and deterioration of insulation are thus prevented. Linen filters take up a good deal

* From 90-100 cu. ft. of free air per min. per kW of loss, or 5 cu. ft. per min. per kW of generator capacity; say, 75 000 cu. ft. per min. in the case of a 15 000 kW alternator.

of room and need periodical cleaning; should they be set on fire, the generator may be damaged before a safety door and fusible link combination in the air-duct has time to act. Water-spray filters are more compact; they are very effective, offer minimum resistance to air-flow, need a minimum of attention, and are more economical where large plants are concerned. Air is cooled as well as filtered by the waste spray apparatus, and the moisture imparted to the air is no disadvantage so long as actual drops of liquid are not carried forward in suspension. Another type of filter which gives good results consists of a chamber filled with short lengths of metal tubing (about 1 in. long × 1 in. dia.); these tubes are jumbled so that air flowing through the chamber has to follow a tortuous path, in the course of which all dust is retained by the film of non-drying oil with which the tubes are coated. The tubes are cleaned and re-coated at intervals of some weeks or months as required.

In the 40 000 kW alternators of the Gennevilliers station,* the ventilating air is in a closed circuit. This eliminates the problem of filtering huge volumes of air. Condensate from the turbine condenser is passed through an air-cooler which cools the ventilating air and returns the heat of the latter to the boiler, thus improving the overall efficiency.

The temperature rise of air passing through the generator may be calculated from the formula—

Temperature rise (° F.) = 2 916 × kW loss / cu. ft. of air per min. Allowing 100 cu. ft. of air / min. / kW loss, the temperature rise is approximately 30° F.

The warm air could be led to the boiler furnaces and would result in about 1 % increase in overall thermal efficiency; this does not offer a very promising return on the capital and maintenance costs of the ducts required.

The problem of dissipating the losses in large turbo-generators is simplified by the use of water instead of air as a cooling medium because the specific heat of water is 1·0 compared with 0·24 for air, *i.e.* 1 lb. of water removes more than four times as much heat as 1 lb. of air for the same temperature rise. In the Parsons water-cooled alternator rotor, water is fed to a central passage bored along the axis of the solid rotor forging. Thence, the water passes through radial holes at one end of the rotor to weldless

* *El. Rev.*, Vol. 92, p. 604.

steel tubes embedded at the bottom of the winding slots; hot water is collected from these tubes by radial holes at the other end of the rotor and cooled for recirculation. The more extensive use of water cooling in turbo-generators is discussed by J. Shepherd, *Jour. I.E.E.*, Vol. 58, p. 125.

147. Voltage Regulation.—Whereas in a D.C. generator the alteration of pressure between no-load and full-load is independent of the character of the load, this is not so in an alternator. The British standard definition * of the regulation of an alternator is as follows:—

> The normal inherent regulation of an alternator is the rise in pressure from rated output, at the specified power factor and rated pressure, to no-load, with constant speed and excitation; the rise in pressure is the difference between the pressure at rated output and at no-load stated as a percentage of the rated pressure (B.E.S.A. Report No. 72).

The actual value of the inherent regulation varies with the power factor of the load (§ 155), and increases with the reactance of the alternator windings. Formerly it was usual to specify close inherent voltage regulation (say, 5 %) but this involved low reactance in the alternator and resulted in the current rising to 20 or more times the normal value in the event of short circuit. Apart from the excessive heating caused by such a current, should it endure, there are produced enormous mechanical forces (§ 338) which may wreck the machine. For these reasons, and because the parallel operation of synchronous machinery is more stable when there is considerable reactance in the circuit, it is now usual to employ alternators of high internal reactance; choking coils are also placed in series with the generator phases for protective purposes (§ 340). A method of determining the inductance of alternators is given in Chapter 40.

With constant excitation the voltage of a modern alternator would drop by from 6-10 % from no-load to full-load if the latter were a non-inductive lighting load, and by from 20-25 %

* The regulation thus defined is often called the "regulation up" in distinction from the "regulation down," which is an alternative (non-standard) definition of regulation as the drop in voltage from no-load to full-load expressed as a percentage of the no-load voltage, the speed being constant and the excitation being constant at the value required to produce rated voltage at no-load. A given percentage regulation is obtained more easily and cheaply when the standard (regulation up) definition is employed.

or more * if the load were of power factor 0·8. In practice the voltage is kept constant, or raised with the load, by altering the excitation of the field. If the load variations be gradual, the field regulation may be effected by hand or by a servo-motor controlled by a contact-making voltmeter. Generally, however, an automatic voltage regulator is employed. There are many types of these regulators in use, differing considerably in construction,† but they all operate by varying the field current of the exciter (§ 140) and so the excitation of the alternator. A solenoid connected between two of the leads from the generator produces a pull which increases or decreases with the generator voltage; if required the solenoid can be 'compounded' by a coil carrying a fraction of the main current and opposing the action of the voltage coil so as to increase the generator voltage with increasing load. The pull of this solenoid is utilised to vary the resistance in the exciter field circuit. Complications in electrical and mechanical construction are required to secure rapid action and to prevent the alternator voltage from 'hunting' above and below normal, but these do not affect the principle of operation.

148. Parallel Running of D.C. Generators.—So long as they are of approximately the same construction and designed for the same pressure, any two or more shunt-wound dynamos may be connected in parallel, *i.e.* to supply energy to the same circuit, without any particular difficulty or risk. If two such generators be exactly similar, and if both yield the same E.M.F. at any particular load, each machine will take half the total load. If one should take temporarily more than its fair share of the load for any reason, its E.M.F. would fall below that of the other dynamo (for the voltage of a shunt dynamo decreases with increasing load, *see* Fig. 30, § 138), and hence the state of balance would be restored automatically. The terminal potential difference

* In the 40 000 kW alternators at Gennevilliers (§ 196) the voltage drop between no-load and full-load at 0·8 power factor is 33·3 %. The stator slots are designed so that the magnetic leakage is particularly high; the inductive drop due to leakage is, with normal current, 24 % of the normal pressure (10·2 % due to the slot leakage and 9·5 % to the end connections). The short-circuit current of these machines is only about 4·2 times normal full-load current. (*El. Rev.*, Vol. 92, p. 604.)

† For descriptions *see* C. C. Garrard, *The Electrician*, Vol. 74, p. 107, and Whittaker's *Electrical Engineer's Pocket Book*, 5th ed., p. 434; *also* H. N. George, *British Westinghouse Gazette*, Vol. 4, p. 206.

of a shunt dynamo is $V = (E - IR)$ volts, where E is the E.M.F., I the armature current, and R the armature resistance. If two shunt generators having equal E.M.F. operate in parallel, the terminal P.D. is the same for each, hence $(E_1 - I_1R_1) = (E_2 - I_2R_2)$. In other words, $I_1 / I_2 = R_2 / R_1$, *i.e.* the generators share the load in inverse proportion to their armature resistances, so long as the E.M.F. $E_1 = E_2$; to distribute the load in other than this proportion, E_1 or E_2 is varied by shunt field regulation. If I_2 increases, E_2 is reduced (Fig. 30), so that the normal state of affairs is quickly restored. If the speed of machine No. 1 falls, E_1 decreases, hence I_1 decreases as well, to keep the difference $(E_1 - I_1R_1)$ constant. By weakening the field and decreasing the speed of one dynamo its E.M.F. may be made lower than the terminal P.D. of the other machine. In that event the first machine runs as a shunt motor, but does not take an excessive current (*cf.* series generators below).

In the case of two series generators working in parallel, we must still satisfy the condition $V = (E_1 - I_1R_1) = (E_2 - I_2R_2)$. So long as this is done, the generators work satisfactorily in parallel, but if the current through one dynamo, say I_2, increases beyond the value satisfying the above equation, the E.M.F., E_2, of that machine *increases* (Fig. 31). Simultaneously, however, I_1 and therefore E_1 will have decreased, so that a yet bigger share of the load now falls on the second machine, *i.e.* I_2 and E_2 increase yet further, and so on until this machine carries the whole load. The most serious trouble occurs after that, for the unloaded dynamo then begins to run as a series motor, and we have a series dynamo practically short-circuited on a series motor, with the result that both machines burn out. The only way to prevent this action is to interconnect the armature-field connections of the two machines (*i.e.* the brushes to which the series field windings are connected) by an 'equalising' conductor. In order that the latter may be effective, it is essential that its ohmic resistance be low as compared with that of the field coils, which are themselves of low resistance.

From these remarks it will be seen that D.C. generators having a drooping voltage-current characteristic can be operated stably in parallel without any trouble, whereas generators with a rising voltage-current characteristic are inherently unsuitable for parallel operation. Compound-wound dynamos, with rising or

flat characteristic curve, require an equalising circuit for stable operation in parallel; this is run between the positive brushes of the various machines when working. Each equaliser bar has a switch which must be closed before the machines are paralleled, and kept closed so long as the machine to which it corresponds is working in parallel with one or more others.

In most central stations shunt-wound generators are used, even though batteries be not installed. As explained in § 138, the field of a shunt dynamo is generally built up from residual magnetism in the iron, but this magnetism may be so weak that the generator is incapable of self-excitation, or it may be reversed so that what was the positive brush one day becomes the negative brush next day. It is therefore customary to excite the magnets from the bus bars before putting a machine in circuit; this ensures correct polarity. When starting a plant for the first time, it may be necessary to excite the magnets from a small battery till the building-up process gets under way. So long as the polarity is correct, the incoming machine can be switched in parallel directly its E.M.F. is equal to or (to allow for the drop occurring directly the machine takes load), a little above, that of the machines already in service. Thereafter load is distributed between the machines automatically or by field regulation, as already explained. If a compound-wound generator refuses to excite normally, it can generally be made to do so by *momentarily* short-circuiting the main terminals—assuming, as in the case of the shunt machine, that the connections are correct and that the brushes are down on the commutator. This short-circuiting is best effected by a small-diameter copper wire put between the terminals before the machine is started; the wire fuses before the short-circuit current reaches a dangerous value. After closing the equalising switch and bringing up the pressure of the incoming machine, the main switch is closed and parallel running established.

149. Parallel Running of Alternators: Synchronising and Synchroscopes.—Alternators of all types and sizes, provided they are wound for the same number of phases and cycles, and for the same pressure, can be run in parallel, but it is preferable that their wave forms should be similar;* the 3-phase plant in

* B.E.S.A. Report No. 72 requires that the wave form of an alternator on open circuit shall approximate to a sine wave. The maximum deviation of the actual wave from the equivalent sine wave (same R.M.S. value and same wave

two hydro-electric stations over 350 miles apart, in California, is feeding the same network in this way. The most satisfactory parallel working is obtained when the alternators are driven by steam turbines, as the turning moment of these during each revolution is absolutely regular; this is not the case with reciprocating engines, although by scientific balancing of the rotating parts, and the use of heavy flywheels, a fair approximation to an even turning moment can be obtained. Even in water turbines there is some periodic variation in turning moment, especially in impulse turbines where the tangential force may vary in the ratio 1 : 2 as the bucket passes through the jet. If through any such irregularity the machines get slightly 'out of step' the magnetic effect of the interchange currents set up between them pulls them back again into synchronism. It is not uncommon, however, for trouble to be experienced in the way of heavy interchange currents between alternators connected in parallel and driven by steam turbines and horizontal reciprocating engines respectively. Such trouble is due to difference in the 'cyclic irregularity' of speed * of the two prime movers, and may generally be cured by increasing the flywheel effect of the engine-driven alternator. The actual behaviour of machines in parallel depends upon the mechanical constants of all the machines; in some cases two sets may not run well in parallel but each may run satisfactorily in parallel with a third set. Much information on the hunting of alternators in parallel is given by J. Fischer-Hinnen, *Electrician*, Vol. 89, p. 185.

Synchronising and Synchroscopes.—When it is desired to connect another machine into circuit with those already running on load, it is brought up to about the correct speed and the field strength is varied until the voltage, at that speed, is approximately the same as that on the bus bars; it is then necessary to get the successive waves of E.M.F. on the incoming machine into exact synchronism with those already working on the load, so that the periodicities are precisely equal and also the crests of

---

length), when superimposed on it so as to give the least difference, should not exceed 10 % of the maximum ordinate of the sine wave.

* The cyclic irregularity of a prime mover is generally defined as the ratio of the difference between the maximum and minimum angular speeds to the mean angular speed of the driving shaft during one revolution. This ratio should not exceed 1 / 150 and is generally lower.

corresponding waves are attained at the same instant. In the early days of alternating current working this was a troublesome matter, and the moment of closing the paralleling switch was an anxious one; at the present day instruments known as synchronisers or synchroscopes render the operation simple. Of these there are a number of types in use, employing either (*a*) a lamp or a voltmeter, or (*b*) a dial and needle to indicate when the exact coincidence of phase occurs. In the former type the lamp or voltmeter is connected to the secondary of a small transformer, having two primary windings connected to the machine and bus bars respectively; the windings are so designed that only when the two primaries are exactly together will the resulting secondary pressure be high enough to light the lamp. As synchronism is approached the lamp lights up and then becomes dark at longer and longer intervals, and when it remains at full brightness the connecting switch is closed. The machines, however, may be as much as 16 (electrical) degrees out of phase before the synchronising voltmeter shows 1 $^{\circ}/_{\circ}$ variation from its maximum reading, so that a little error of judgment may result in a considerable shock when switching in, while there is nothing to show which machine is the faster.

Dial instruments consist either of a miniature induction motor or of a dynamometer movement; the needle revolves in one direction or the other according to whether the speed of the incoming machine is too high or too low. When the needle becomes stationary the machines are in step. Maintained identity of phase implies equality of frequency, hence it is unnecessary to use a frequency meter (§ 112) for synchronising.

In the Weston synchroscope (Fig. 38) the moving element consists of a very light dynamometer movement pivoted between jewels and connected through a condenser across the terminals of the incoming machine. The fixed coil, which is wound in two sections, is connected across the line through a resistance. The pointer is behind the translucent glass scale, which is illuminated by a lamp connected to the central coil of a transformer, having two primary coils connected across the bus bars and the incoming machine respectively, so as to glow brightly when the machines are in synchronism; thus *only* when the lamp is alight is the shadow of the pointer seen. As the one circuit contains a condenser and the other a slightly inductive resistance, it is possible

to adjust their constants so that the currents in the two will be in exact quadrature when the E.M.F.'s are either in phase or in opposition, and under these conditions no torque will be exerted and the pointer will stand in the centre of the scale. Since the lamp is dark when the E.M.F.'s are in opposition and light when they are in coincidence and have the same frequency, the shadow

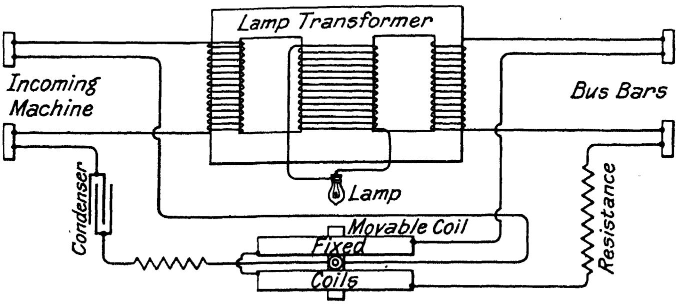


FIG. 38.—Connections of Weston synchroscope.

of the pointer will be seen at rest in the middle of the scale when perfect synchronism is attained. But when the E.M.F.'s are not exactly in phase or in opposition, there will be a torque tending to turn the movable coil, and the value of this torque will increase with the phase displacement, its direction depending upon the relative direction of the currents in the coils. If the machines are not running at the same frequency the torque will vary continuously from zero to plus maximum and back through zero to minus maximum, thus causing the pointer to swing back and forth over the scale (Fig. 39). Each swing will coincide with a period of light or darkness, and the pointer will be seen only during every other swing, that is, it will appear to rotate in one direction. The direction of this apparent rotation indicates whether the incoming machine is fast or slow, and the speed of rotation is a measure of the amount by which the frequencies differ. It is clearly better to switch in when the incoming machine is slightly ahead of those already connected, or on a 'rising phase;' the machine will then drop into phase as it takes up load instead of having to be pulled in.

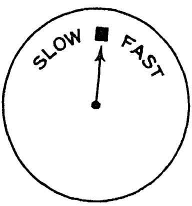


FIG. 39.—Dial of synchroscope.

The Everett-Edgcumbe synchroscope uses a similar indicating

dial to that last described, but the moving needle is connected to the rotor of a miniature 2-phase motor, in which one set of windings is fed from the bus bars and the other set from the incoming machine. If the bus bar frequency is the same as that of the incoming machine these fields will rotate in step, and the rotor will remain at rest. If, however, the frequency of the current in one set of coils is higher than that in the other set, then the tendency of the two fields to keep in step will cause the rotor to revolve in the same direction as the fields, and thus indicate 'fast' or 'slow.' A red or green lamp, visible from the stop valve, is shown in the opening behind the needle, according to whether the incoming machine is running fast or slow; and, by a relay, similar lamps can also be placed at each prime mover when the synchroniser is out of sight.

Automatic paralleling gear is used in some stations, and its use will probably extend with the increasing adopting of automatic hydro-electric generating plant (§ 187) and automatic substations (Chapter 17). The utility of this gear probably lies in eliminating continuous attendance in isolated installations rather than in offering greater security where skilled staff is available. The apparatus is rather complicated and delicate but the principle of operation is simple; a series of relays close when there is equality of voltage, phase, and frequency in the two circuits to be paralleled, and the paralleling switch is then closed automatically.

After parallel running is established the load is divided between the various machines by hand regulation of the throttle valve or by the governor; in large generating stations the governors of steam or water turbines can generally be adjusted from the switch-board, through the agency of a small servo-motor.

150. Phase Connections and Phase Rotation.—In the case of 3-phase alternators, it is necessary initially to connect the phases correctly to the switchboard, so that armature coils which occur consecutively in the direction of rotation of one machine are in parallel with coils occurring in the same relative position in other machines. Various conventions are used to identify phases, *e.g.* red, yellow or white, and blue, with green for the neutral wire, the colours being used to mark terminals and wires and to show the direction of rotation of the field due to successive waves. (*See also* I.E.E. rule 51, § 280.) The standard method of numbering phases with regard to sequence is shown in Fig. 16,

§ 110. A reference to Fig. 4 (§ 15) will show that if the waves do not run in order and as shown, owing to one coil being connected wrongly, the symmetry of the system will be upset and a short-circuit will occur. So long as there are fine fuses in circuit no harm will result from trial and error in making the connections; two terminals are therefore connected together and the resultant voltage across the open ends of these coils is measured under working conditions. If the connection is in delta and correct this should be the same as the voltage between the ends of either coil alone. Obviously this is so, as the third coil (also giving the same pressure) is to be connected across these terminals (Fig. 36, § 143); this is done through a fine fuse, which will blow if the connection is wrong. In the case of star connection (Fig. 37) the same procedure on the first two coils will show a resultant

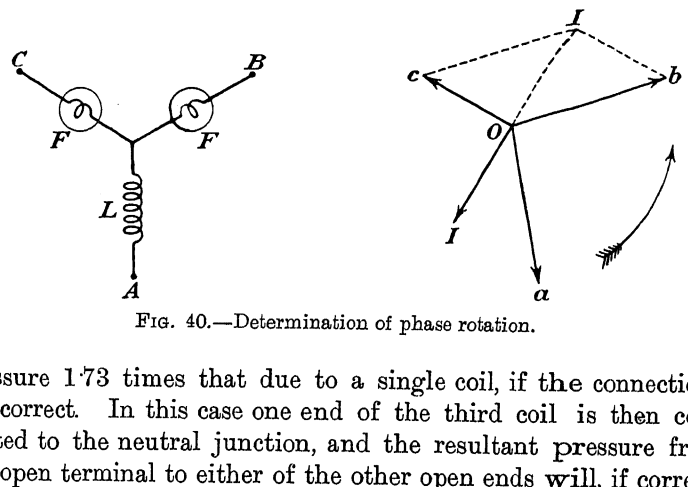


FIG. 40.—Determination of phase rotation.

pressure 1·73 times that due to a single coil, if the connections are correct. In this case one end of the third coil is then connected to the neutral junction, and the resultant pressure from the open terminal to either of the other open ends will, if correct, give the same result.

The phase rotation of two alternators may be compared by connecting a motor to each in turn, and noting which connections cause the motor to run in the same direction in both cases; these connections are in the same phase rotation. Miniature 3-phase induction motors are made for this purpose with disc armatures.

A method of determining phase rotation, due to Varley, is illustrated by Fig. 40. Two similar filament lamps F, F and an inductance L are connected in star between the phases ABC to be identified. If Oa represent the voltage across the inductance

L, the current through the latter is represented by the lagging vector OI (§ 44). The equal but opposite vector OI' represents the resultant of the currents Oc, Ob, through the lamps. Since the latter are practically non-inductive the P.D. across each is in phase with the current. Now Ob is greater than Oc, hence the lamp in the B phase will glow more brightly; this phase is lagging with regard to C, and the phase rotation is as shown by the arrow. Hence the rule: The lamp connected to the lagging phase glows more brightly. (*See also* Dransfield voltmeter, § 100.)

Kapp's method of deducing the sequence of phases from wattmeter readings is explained *Jour. I.E.E.*, Vol. 55, p. 309.

The connections of synchroscopes can be verified (after checking the phase sequence as above), by disconnecting the phases of the new machine at the neutral point and switching this machine (*whilst stationary*) on to the live bus bars. Both sides of the synchroscope are then excited from the bus bars and, if the connections are correct, synchronism is indicated. Where bus bars are sectionalised it must be made impossible to parallel machines which are in synchronism with different sections of the bus bars.

151. Official Regulations.—The Electricity Regulations of the Factory and Workshop Acts, 1901-1911, contain the following clauses:—

19. All parts of generators, motors, transformers, or other similar apparatus, at high pressure or extra high pressure, and within reach from any position in which any person employed may require to be, shall be, so far as reasonably practicable, so protected as to prevent danger.

21. Where necessary to prevent danger, adequate precautions shall be taken either by earthing or by other suitable means to prevent any metal other than the conductor from becoming electrically charged.

25. Adequate working space and means of access, free from danger, shall be provided for all apparatus that has to be worked or attended to by any person.

The complete text of these Regulations and the official Memorandum thereon should be studied.

Concerning the location and protection of dynamos, I.E.E. rule No. 123 specifies as follows:—

123. Dynamos (Rule 36, § 269) (*see* British Standardisation Rules for Electrical Machinery, Report No. 72*) must—

(*a*) *Inflammable Dust.*—Not be placed in positions exposed to inflammable dust or flyings, nor where combustible materials are manipulated or stored;

* In part replaced by No. 168; see § 136 *supra.*

(b) *Protection.*—Be protected from damp, dust, and mechanical injury;
(c) *Combustible Materials.*—Be so placed that no unprotected woodwork, or other combustible material, is within a distance of 12 ins. from them measured horizontally, or within 4 ft. measured vertically above them;
(d) *Wood Floors.*—Have a sheet of metal inserted between them and such flooring, where mounted upon or above wood flooring;
(e) *Control.*—Be controlled by a double-pole switch and protected by a fuse, or circuit-breaker, on each pole, except with earthed concentric wiring.

152. Bibliography (*see* explanatory note, § 58).

REGULATIONS.

H.O. Electricity Regulations for Factories and Workshops (§ 150).
H.O. Regulations as to Installation and Use of Electricity in Mines (Chapter 32).
I.E.E. Wiring Rules (§ 150).

STANDARDISATION REPORTS, ETC.

(1) *I.E.C. Publications.*
No. 34. Rules for Electrical Machinery.

(2) *B.E.S.A. Reports.*
No. 72. British Standardisation Rules for Electrical Machinery.
No. 96. Parallel-sided Carbon Brushes for D.C. Commutator Machines.
No. 168. British Standard Specification for the Electrical Performance of Industrial Electric Motors and Generators.

(3) *B.E.A.M.A. Publications.*
Standardisation Rules for Electrical Machinery.

BOOKS.

Primary Batteries; their Theory, Construction, and Use. W. R. Cooper (Benn).
Electrical Characteristics and Testing of Dry Cells. Circ. No. 79, Bureau of Standards (Washington).
Modern High Speed Influence Machines. V. E. Johnson (Spon).
Dynamo-Electric Machinery. S. P. Thompson, 2 vols. (Spon).
The Dynamo. L. G. Hawkins and F. Wallis, 2 vols. (Pitman).
Continuous Current Armature Winding. F. M. Denton (Pitman).
Elementary Principles of A.C. Dynamo Design. A. G. Ellis (Blackie).
Specification and Design of Dynamo Electric Machinery. Miles Walker (Longmans).
D.C. Dynamo and Motor Faults. R. M. Archer (Pitman).

I.E.E. PAPERS.

Too numerous to be mentioned; papers have been published on all phases of the subjects discussed in this Chapter.

CHAPTER 5.

POWER FACTOR AND ITS IMPROVEMENT.

153. Lagging and Leading Power Factors.—The power factor of an A.C. circuit may be defined as the ratio of the true watts to the volt-amperes or apparent power (§ 56). In other words, it is the factor by which the volt-amperes must be multiplied in order to obtain the true watts.* When the current wave is out of phase with the voltage wave the power factor is less than unity; to discriminate between the two cases, a power factor of, say, 0·8 or 80 %, may be termed '0·8 lagging' if the current waves lags behind the voltage wave, and '0·8 leading' if the current wave leads with regard to the voltage wave. With few exceptions, the P.F. of industrial A.C. circuits is lagging, and when a simple numerical value is stated for the power factor it may generally be assumed to be lagging. The ideal condition in an A.C. system is that of unity power factor and, *compared with unity power factor, any lower power factor is equally objectionable whether leading or lagging.* In practice, A.C. loads having a low and leading P.F. are generally welcomed because the resultant P.F. of the system is usually less then unity and lagging, hence the addition of circuits having a leading P.F. improves the P.F. of the system as a whole (§ 159).

154. Watt and Wattless Components.—In order to appreciate the consequences of low-power factor it is necessary to consider the "composition" of the current under such conditions. Taking the case of a lagging current, as being that generally encountered in practice, the current OI (Fig. 41) lags $\phi°$ with

* This simple definition is equally applicable to single-phase circuits and to balanced polyphase circuits, but the interpretation of the definition is complicated in the case of unbalanced polyphase systems in which the currents in the several phases, and the phase angles between these currents and their voltages are not equal. Alternative definitions, and methods of calculation and measurement to be employed in such circuits are discussed in a symposium, *Jour. Amer. I.E.E.*, Vol. 39, pp. 538-46; *see also* § 111.

regard to the voltage OE, and may be resolved into a watt (or active) component OA ($= I \cos \phi$) in phase with the voltage (*see* Fig. 8, § 37), and a wattless (or reactive) component OB ($= I \sin \phi$) 90° out of phase with the voltage (Fig. 9, § 37). The power factor $= \cos \phi$. An equal current OI' at a greater angle of lag ϕ' (*i.e.* a lower power factor) has a smaller watt component OA' and a larger wattless component OB'. For the same watt component as before (OA), we must increase the total current to OI'' when the lag is ϕ', the wattless component then increasing to OB''. It should be noted that it is the *vectorial* sum of OA and OB which equals OI, *i.e.* the total current and its components form the three sides of a right-angled triangle, and

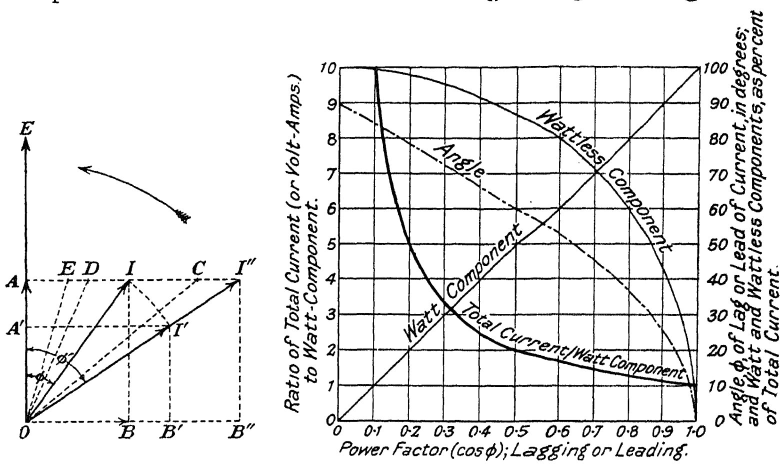


FIG. 41.—Watt and wattless components of current at various power factors.

the *arithmetical* sum of the components is always greater than the total (actual) current.

These points are illustrated by the curves plotted in the right-hand portion of Fig. 41, against a base of power factor. The curve representing the angle of lag or lead corresponding to various power factors is a cosine curve (P.F. $= \cos \phi$). The watt component, as a percentage of the total current, is directly proportional to the power factor and is, therefore, represented by a straight line. The wattless component is proportional to sin ϕ, and, when plotted against power factor, gives a curve which is a quadrant of a circle. It will be seen that when the P.F. is 0·95, the watt component is 95 A and the wattless component about

31·3 A for every 100 A total current; and at 0·65 P.F. (not an uncommon value in practice, § 157), the watt component is 65 A and the wattless component 76 A for every 100 A total current.

The value of the ratio: Total current / watt component = $\sec \phi = 1 / \cos \phi$, and rises from unity at unity P.F., at first gradually and then very rapidly, to infinity at zero P.F. as shown by the heavy curve in Fig. 41.

155. Effects of Low-power Factor.—From the preceding remarks and by inspection of the vector diagram in Fig. 41, it is obvious that the current OI is always greater than its watt component OA. In other words, for the same useful power (true watts) as represented by the voltage OE and the current OA in phase with it, we require a larger current OI if the angle of lag be ϕ, and a yet larger current OI'' if the lag be ϕ'. The larger the angle of lag, the lower the power factor, and the larger the current required for given true power. The current-carrying capacity of the generators, transformers, and transmission lines (§ 301) must therefore be higher, the lower the power factor for a given load (kW); or, the dimensions of the generators, etc., being fixed, the kW which can be supplied is lower, the lower the power factor. We thus arrive at the most obvious—and generally the most important—effect of low-power factor, *viz.* reduced kW capacity of the whole of the electrical equipment and, hence, increased standing (capital) charges on every unit (kWh) of energy delivered. If the kW output of the generators, when working at the maximum safe kVA output, is less than the kW capacity of the prime movers,* part of the investment in the latter is non-productive and there is a further increase in the standing charges per kWh. The working costs are also increased by the fact that the I^2R losses (§ 49) in all parts of the circuit vary with the square of the *total* current (*i.e.* inversely with the square of the power factor); as the total current is 1·43 times the watt component when the P.F. is 0·7 (*see* heavy curve, Fig. 41), the I^2R losses are then $(1{\cdot}43)^2 = 2{\cdot}05$ times as great as though the same useful load were supplied at unity P.F. The wattless component itself absorbs no energy from the prime movers for its production (§ 37),

* On the assumption that the maximum P.F. likely to be reached in the system as a whole at full-load will be 0·8, it is usual to make the kW capacity of prime movers equal to 80 % of the kVA capacity of the generators to which they are coupled.

but it takes up current-carrying capacity which might otherwise carry useful power, and the additional I^2R-loss due to wattless current represents a dissipation of energy which has to be supplied by increased output from the prime movers.

At low-power factor (which is particularly prevalent during light-load periods), the generators and other parts of the electrical system are electrically fully loaded at a fraction of the rated kW output of the prime movers, hence the steam, fuel, or water consumption of the latter is higher per kWh than it would be if the same useful load were supplied, at higher power factor, by a smaller number of generators, the prime movers of which could then be fully loaded.

The heavier total current, corresponding to a given watt component, at lower P.F. involves a greater IR drop (§ 24) in the ohmic resistance of the circuit. In addition, the inherent voltage regulation of generators and transformers is worse, the lower the P.F. The voltage regulation of a transformer may be 1 % at unity P.F. and 3-5 % at 0·7 P.F.; that of a modern alternator with windings of high reactance may be 10 % at unity P.F. and 20-25 % at 0·8 or 0·7 P.F. (§ 147). There is no means in the transformer of compensating for the additional voltage drop with low-power factor. The alternator voltage is held constant by increasing the excitation (§ 147); at the best, operation at low P.F. means that the exciter output must be increased (and the generator efficiency thus reduced), and it may happen that the alternator field coils reach their limiting temperature before the excitation is increased sufficiently to maintain normal voltage—in that event the kVA, as well as the kW, capacity of the alternator is reduced at the lower power factor. At 0·8 P.F. the field current must be about 50 % heavier than at unity P.F. to maintain normal voltage and equal kVA output.

The net effect of the increased losses and lower kW capacity at lower P.F. is an appreciable decrease in efficiency in the electrical system. At 0·8 P.F. and rated kVA output the efficiency of alternators is about 2 % lower, that of transformers ¾ % lower, and that of transmission lines 2-3 % lower than at unity P.F. These reductions in efficiency involve higher fuel costs per kWh delivered.

156. Causes of Low Power Factor.—The prevailing power factor of all commercial supply systems being lagging (§ 153), it

may be taken that any increase in inductive reactance (§ 44) will lower the power factor, whilst any increase in charging current will raise the power factor. The greater the inductive reactance, *i.e.* the greater the inductance and the higher the frequency, the lower the power factor, other conditions being constant. Similarly, the larger the capacity and the higher the frequency, the higher the power factor, other conditions being constant. (*See also* § 135 (1).)

The effects of the inductance and capacity of a line on the power factor are exemplified in §§ 300, 305. The line itself may cause the current to lead or to lag with reference to the E.M.F. according to whether the capacity or the inductance predominates. Underground cables have considerable capacity (§ 311), while inductance is more important in most overhead lines (§§ 299, 305, 306). In the case of long distance, extra high voltage lines, however, the charging current is an important factor and may compensate more or less accurately the inductive drop in the line at full-load (§§ 158, 318, 331); on light load, in such cases, it may be necessary to compensate for the charging current by switching inductances into circuit. At all pressures up to 50 000 V or so, and for all distances up to about 50 miles, the inductance of overhead lines predominates over the capacity effect and causes a reduction in the P.F. of the system.

The magnetising current and magnetic leakage of transformers cause the total current to lag with regard to the E.M.F., but the effect on the P.F. is small at normal load. When a transformer is on light load (secondary circuit open) its primary current is almost entirely wattless; for this reason house-lighting transformers have a very bad effect on the P.F. of the system during the daytime.

Arc lamps have relatively low P.F. due to the characteristics of the arc itself (§ 56), the inductance of the operating coils, and (where used) the inductance of regulating chokers; the P.F. of these lamps is commonly 0·85 for the arc itself and 0·7 or 0·6 including the operating coils and ballast. Filament lamps are practically non-inductive and have themselves no appreciable effect on the P.F., but the more of these lamps there are in use, the higher the average P.F. of the system. If the lamps be used in conjunction with condensers (Chapter 20), the latter cause leading currents and raise the P.F.

Electric heaters are non-inductive if the circuits be so arranged

that the magnetising effect of each wire is neutralised by the equal but opposite effect of an adjacent wire carrying the return current; if this precaution be not taken the apparatus is inductive, to a degree which increases with the proximity and amount of iron near the conductors. Arc furnaces are of relatively low P.F. for the same reason as arc lamps; if the furnace be used to melt iron or steel the circuit is particularly inductive (P.F. 0·6-0·65) until the temperature exceeds that at which iron becomes non-magnetic (§ 84); thereafter, the P.F. may rise to 0·85 or 0·9. The P.F. of induction furnaces (Chapter 38) is very low in the larger sizes because of the low resistance of the secondary circuit; in the largest furnaces of this type a supply frequency as low as 5 cycles / sec. has been used in order to improve the P.F. (§ 135).

Synchronous motors and rotary converters may cause either lead or lag according to circumstances; an over-excited synchronous motor may be used simply to counteract the lag due to inductive apparatus or it may at the same time be doing mechanical work (§ 160 *c*).

By far the most important cause of low-power factor in average industrial supply systems is the induction motor. As explained in Chapter 28 this motor is essentially a transformer, but, due to the high reluctance of its magnetic circuit, it has a large magnetising current and a correspondingly low P.F. The actual value of the P.F. ranges from 0·8-0·85 at full-load to 0·6 or 0·7 at $\frac{1}{2}$-load, and 0·4-0·45 at $\frac{1}{4}$-load in the case of large motors (50-100 h.p.). In small motors, of $\frac{1}{2}$ to 2 h.p., the P.F. may be 0·6-0·7 at full-load, and 0·25-0·3 at $\frac{1}{4}$-load. From these figures it is evident that induction motors should be operated as nearly as possible at full-load. On light-load the current consumption is almost entirely wattless, the power factor is about 0·1, and the kVA input is about one-third of the full-load kVA. Maximum P.F. is reached at about full-load; on overload the P.F. decreases because of the rapid increase in wattless component. The P.F. of high-speed induction motors is higher than that of low-speed machines of equal output (Chapter 28), hence the high-speed motor is to be preferred. The P.F. of single-phase induction motors is generally lower than that of 3-phase machines.

157. Measurement and Estimation of Power Factor.—Power factor indicators or phase meters of various types have

already been described (§ 111). Such instruments are useful in measuring the P.F. of a particular load and in switchboard service, but from § 156 it will be realised that the P.F. is ever varying, both at different times and in different parts of a circuit at any one time. The P.F. meter should therefore be in the form of a recording instrument (§ 93) when any estimates are to be made which involve a knowledge of the average daily power factor.

For project estimating the values given in Table 13 for the

TABLE 13.—*Power Factor at Receiving End of Line with Various Loads, at Full-Load in Each Case.*

	Angle of Lag. ϕ.	Power Factor. Cos ϕ.	Sin ϕ.*
Continuous current	Nil	Unity	Zero
A.C.—Lighting only	18°	0·95	0·31
Mixed, ¾ lights, ¼ motors . .	25¾°	0·9	0·436
Mixed, ¼ lights, ¾ motors . .	31¾°	0·85	0·527
Motor load only . . .	36¾°	0·8	0·6
Ditto, mining work . . .	41¼°	0·75	0·66
Ditto, single-phase . . .	45°	0·7	0·7

P.F. of the load *at the receiving end of the transmission line* will be found sufficiently accurate. The P.F. at the generating end may be nearly equal to these figures if there are no transformers or other inductive apparatus on the way; on the other hand, it will be much lower if there are several transformations. For instance, in a case where there are step-up transformers in the generating station, a transmission line, step-down transformers at the receiving end, distributing transformers beyond these, and in some cases low-pressure house transformers as well, the P.F. on a purely lighting load will be only about 0·65. The P.F. of a circuit containing fairly large 3-phase induction motors, fully loaded, but with two banks of transformers intervening, may be as low as 0·6. A serious error in the predetermination of the P.F. may result in the generators failing to give the required output; they may be giving their full designed pressure and their full-load current, but if these are sufficiently out of phase with one another the actual power in true kilowatts may

* The use of sin ϕ (called the 'induction factor') is explained in §§ 299, 302.

be below the full output required. It is not that the driving power is insufficient, but simply that the I^2R losses, due to the heavy lagging currents, set a definite heating limit to the output. So far as heating effects are concerned it makes no difference whether the current is a 'wattless' current or is in exact phase with the E.M.F. Thus it will be seen that, having assumed a given P.F. at the receiving end, according to the class of load characterised in the list above, each successive link in the chain up to the generating station must then be taken into account, in order to arrive at a final result, *viz.* the P.F. of the whole circuit or system. This will be seen in the examples in §§ 299, 302, 305, 313.

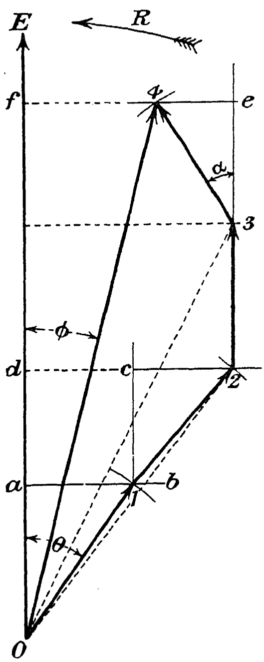


FIG. 42.—Addition of loads of different power factors.

A graphical method * for determining the resultant kVA and P.F. of any group of loads, each of known kVA and P.F., is illustrated in Fig. 42. This figure is arranged consistently with Fig. 41 (§ 154), but the current vector of each successive load is drawn from the end of the preceding current vector.

By way of example assume that the given data are as shown in the left-hand portion of Table 14. The results obtained from the graphical construction are given in the right-hand section of the table, the procedure being as follows: The line *OE* is taken as the axis of E.M.F.

TABLE 14.—*Addition of Loads of Different Power Factors.*

Given Data.			Calculated for Use in Graphical Construction. kW = kVA × P.F.	Results Obtained from Graphical Construction.		
Load No.	kVA.	P.F.		Load Nos.	Combined kVA.	Combined P.F.
1	100	0·80 lag	80	1	100	0·80 lag
2	80	0·75 lag	60	1 and 2	180	0·78 lag
3	75	Unity	75	1, 2, and 3	245	0·88 lag
4	75	0·85 lead	64	1, 2, 3, and 4	290	0·96 lag

* Given by J. A. Van Tilburg, *El. Rev.*, Vol. 90, p. 436.

and the arrow R denotes the direction of vector rotation. In the figure as reproduced the scale of kVA is 100 kVA = 1 in.; greater accuracy would be obtained by drawing to a larger scale.

The vector $O1$ representing the current (and therefore the kVA, the voltage being constant) of load No. 1 is obtained by: (i) Setting out Oa along OE (*i.e.* in phase with the voltage) to represent the *kilowatt* component of the load to scale. In this case kW (= kVA × P.F.) = 100 × 0·8 = 80, which is represented to scale by 80 / 100 = 0·8 in. (ii) Drawing through a a line ab perpendicular to OE. (iii) Drawing, with centre O and radius $O1$ = kVA of load to scale adopted (*i.e.* 100 / 100 = 1 in. in this case), a circular arc to intersect ab at 1. The line $O1$ represents the No. 1 load, the angle of lag being θ and the P.F. = $Oa / O1$ = 0·8.

For the No. 2 load we start from the point 1 and repeat the preceding construction, using the appropriate values for the lines $1c$, $1\text{-}2$. The P.F. of the No. 2 load is $1c / 1\text{-}2$ = 0·75, but the combination of Nos. 1 and 2 loads has P.F. = $Od / O2$ = 1·4 in. / 1·8 in. = 0·78. The kVA of the combined Nos. 1 and 2 loads is represented to scale by $O2$ (= 1·8 in. = 1·8 × 100 or 180 kVA).

The remaining two loads are added in the same way except that No. 3 load (being of unity P.F.) is represented at once by a line 75 / 100 = $\frac{3}{4}$ in. long parallel to OE, starting from 2; whilst for the No. 4 load (which is of *leading* P.F.) the circular arc is struck on the left-hand side of the line $3e$, thus setting the load line 3, 4 at an angle of lead α with regard to the axis of E.M.F.

The combination of the four loads is represented by $O4$, the length (2·9 ins.) of which corresponds to 2·9 × 100 = 290 kVA on the scale adopted. The P.F. of the combined load is $Of / O4$ = 2·8 ins. / 2·9 ins. = 0·96 and is lagging.

The beneficial effect of non-inductive load (No. 3) and leading load (No. 4) in improving the resultant P.F. is shown very clearly in Fig. 42.

158. Avoidance of Low-power Factor.—Though it may be profitable to employ phase-correcting apparatus it should not be forgotten that it costs money to improve an initially low P.F. A much greater net profit is therefore to be derived from the avoidance than from the correction of low P.F.; this truism deserves to be emphasised, because some of the most serious causes of low P.F. (§ 156) can be avoided by suitable choice of apparatus or operating conditions.

In the design of long distance, extra-high voltage overhead lines it is possible to select an operating voltage at which, for the power to be transmitted, the charging current balances the lagging component caused by the inductance of the line (§§ 318, 331). In some cases it might even pay to use underground cable over part of the route, for the sake of the additional capacity effect thus obtainable.

The principal method of avoiding low P.F. in the average industrial supply system lies, however, in the choice and application of motors. Synchronous motors should be used in preference to

induction motors wherever possible; as explained in Chapter 28 there are now available synchronous motors which develop a good starting torque and are self-synchronising. High-speed induction motors should be used in preference to low-speed machines, and no induction motor should be operated at less than its rated output if avoidable (§ 156). In this connection group-driving is preferable to driving by individual motors (see, however, Chapter 29) where induction motors are employed, if the group motor can be operated at nearer its full-load than could individual motors. Often a group of machines can be driven by a synchronous motor (which can also be used for power-factor correction) instead of by individual induction motors. In some cases the use of D.C. motors supplied from a rotary converter or synchronous motor-

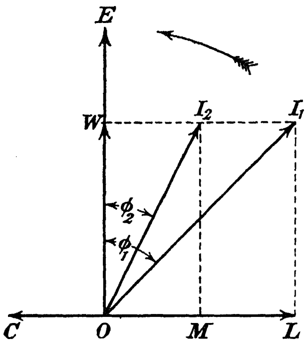


FIG. 43.—P.F. correction with constant kW.

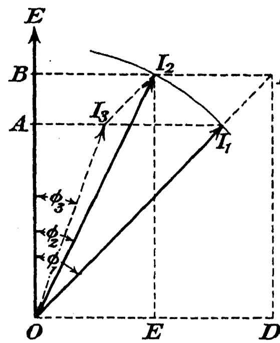
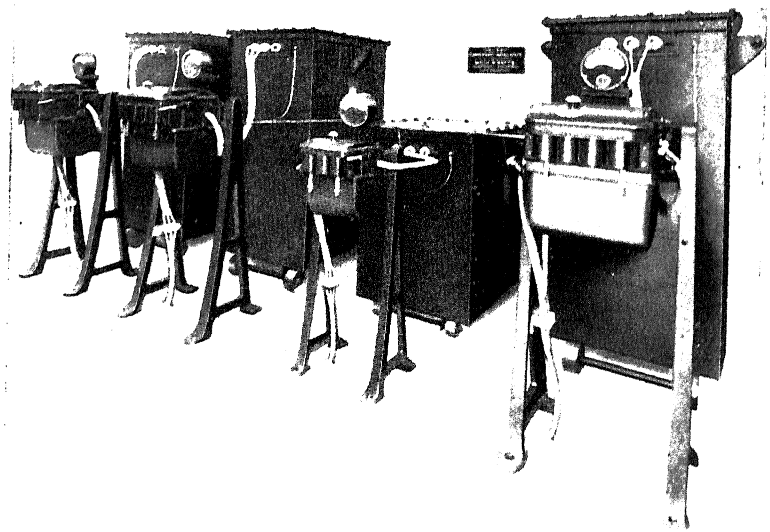


FIG. 44.—P.F. correction with constant kVA.

generator is preferable to the use of A.C. motors throughout a works, because it makes possible higher P.F. at the A.C. supply terminals and also gives the consumer the advantage of variable-speed D.C. motors.

If 3-phase induction motors must be operated for considerable periods at less than $\frac{1}{2}$-load it is worth while to use stator windings which are normally connected in delta, but which can be switched into star connection for operation at low loads. The effect of changing to star connection is to reduce the voltage per phase to $1/\sqrt{3}$ times its initial value (§ 143); the maximum output of the motor varies with the square of the voltage per phase and is therefore reduced to one-third its initial value. With delta-connection the P.F. of the motor might be 0·7 at $\frac{1}{2}$-load and 0·5 at $\frac{1}{4}$-load; with the star connection the values at the corresponding

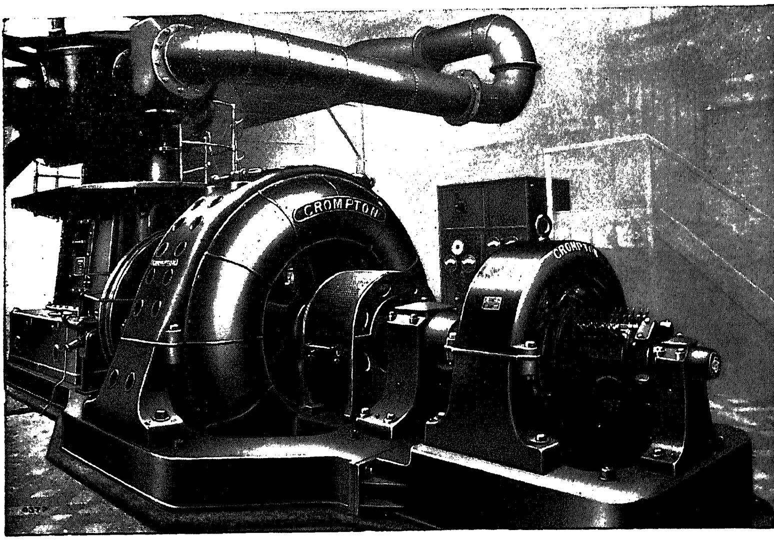


B.I. and Helsby Cables, Ltd.

OIL IMMERSED STATIC CONDENSERS FOR POWER FACTOR IMPROVEMENT.

Static condensers offer the advantage of having no moving parts. They may consist of small box-type condensers used with individual motors or of large tanks. The number in use can be adjusted easily to suit the requirements of the load.

[*To face p.* 228.



Crompton & Co., Ltd.

AUTO-SYNCHRONOUS MOTOR CAPABLE OF BEING USED FOR POWER-FACTOR CORRECTION.

The pure two-phase winding on the rotor (90° phase difference) secures perfect balance and uniform heating during starting and running (*see* Chapter 28). The exciter being connected permanently to the rotor, starting is effected by closing the stator switch and operating the rotor starter. These motors can start against two to three times normal full-load torque, and synchronise automatically, even on overload. If the pull-out torque is exceeded the motor falls out of step but continues to run as an induction motor until the excessive overload is removed, whereupon it synchronises again automatically. The machines can operate at unity P.F., or supply leading reactive power for P.F. correction in the circuit to which they are connected; they are applicable to almost any mechanical drive.

[*To face p.* 229.

H.P.-output would be about 0·9 and 0·85 respectively. At the same time, there would be an improvement in efficiency at the fractional loads.

159. **Principles of P.F. Correction.**—The P.F. correction of a particular load or group of loads of constant kW is illustrated by Fig. 43 in which OI_1 represents the initial current, lagging ϕ_1 with regard to the E.M.F. and having a watt component OW and a wattless lagging component OL. If we add a wattless leading component OC, the net lagging component is reduced to OM ($LM = OC$) and the resultant current is OI_2 which is less than OI_1 and lags by a smaller angle ϕ_2. The P.F. is thus raised from $\cos \phi_1$ to $\cos \phi_2$, *i.e.* from 0·7 to 0·89 in the case illustrated, by the provision of a correcting (leading) kVA represented by LM and here equal to 0·5 in. / 1·43 in. or 0·35 of the initial (uncorrected) kVA represented by OI_1; the same result can be read from the chart Fig. 45.

In practice, the fact that the total current was reduced from OI_1 to OI_2 (Fig. 43) by the improvement in P.F., would naturally lead to the addition of more useful load to the system until the total current again reached its initial value. This case is represented by Fig. 44, in which $OI_1 = OI_2$ and I_1I_1' represents the additional load (assumed to be at the *uncorrected* P.F., $\cos \phi_1$) which can be added to the system in order that the current loading of the latter may remain at the initial value OI_1 *after* P.F. correction to $\cos \phi_2$. In this case the corrective kVA is represented by DE and is 0·65 in. / 1·43 in. or 0·45 of the constant kVA represented by OI_1 or OI_2. The corrective kVA required is naturally greater than in the constant kW case illustrated by Fig. 43, but we have now an increase AB in the kW supplied by the same total current in the mains.

The construction for Fig. 44 is as follows: Draw OI_1 and OI_2 ($= OI_1$) to represent to scale the constant kVA (or current) at the initial and desired final angles of lag ϕ_1, ϕ_2 respectively. Produce OI_1 to intersect at I_1' the line BI_1' drawn through I_2 perpendicular to OE. Then $I_1' I_2$ ($= DE$) represents to scale the required corrective kVA.

This construction amounts to increasing the uncorrected load to OI_1' and then correcting (at constant kW represented by OB, *cf.* Fig. 43) to the load OI_2 which equals OI_1 but is at higher P.F. The same result is obtained by assuming OI_1 to be corrected to OI_3, at an angle of lag ϕ_3 less than ϕ_2, the extra load $I_3 I_2$ at the initial lag ϕ_1 being then added (as in Fig. 42) with the result that the final load $= OI_2$ at lag ϕ_2. In Fig. 44, $\cos \phi_1 = 0·7$; $\cos \phi_2 = 0·885$; $\cos \phi_3 = 0·935$;

if these values be used in the formulæ given below the same results will be obtained as from the graphical construction.

The 'correcting' kVA required to improve the power factor by a given amount increases rapidly as the power factor approaches unity. The reason for this is evident from Fig. 41, § 154. Referring to the curves therein, it will be seen that the power factor increases very slowly as the angle of lag or lead is reduced below, say, 20°; conversely, the wattless component increases very rapidly as the P.F. decreases, and to increase the P.F. from 0·95 to unity it is necessary to neutralise a wattless component which is numerically equal to 31·3 % of the total (uncorrected) current. The same point may be illustrated more clearly by reference to the vector diagram of Fig. 41. The currents OI'', OI, OE have all the same watt component OA; if an equal corrective wattless component $I''C = ID = EA$ be applied to each the percentage improvement in P.F. is much greater in the case of the low P.F. current OI'' than in the currents of higher initial P.F. Thus:—

Current Vector (Fig. 41, § 154).	Angle of Lag, ϕ.		Power Factor (Cos ϕ).		Percentage Increase in P.F. Due to Same Corrective Component in Each Case.
	Initial.	Corrected.	Initial.	Corrected.	
OI″	57°	51°	0·545	0·629	15·4 %
OI	36½°	28½°	0·804	0·879	9·3 %
OE	16°	Zero	0·961	1·000	4·0 %

The corrective kVA or compensation of wattless component required to improve the power factor from an initial value A to a corrected value B (decimal values, *not* percentages) is given in terms of the initial kVA by the following formulæ:—

CASE (1) CONSTANT-KILOWATTS (as in Fig. 43).

$$\text{Corrective kVA} = \left[\sqrt{(1 - A^2)} - \frac{A}{B}\sqrt{(1 - B^2)}\right] \times 100\ \%$$

of initial (*uncorrected*) kVA.

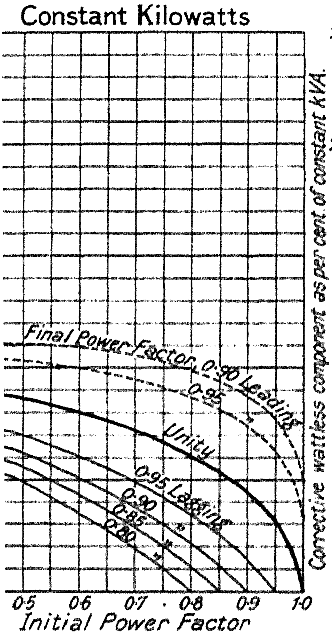
CASE (2) CONSTANT-KILOVOLT-AMPERES (as in Fig. 44).

$$\text{Corrective kVA} = \left[\frac{B}{A}\sqrt{(1 - A^2)} - \sqrt{(1 - B^2)}\right] \times 100\ \%$$

of the (constant) kVA of the system.

The curves plotted from these formulæ in Figs. 45, 46 will

areful study. The much greater corrective kVA required ige the P.F. from 0·95 lagging to unity or from unity to .ding, compared with the corrective kVA required for the ·05 increments in power factor is shown very clearly in ts of curves. The corrective wattless component required ed change in P.F. is naturally greater when the total kVA ant, than when the kW is constant; this is particularly ole when the initial P.F. is low. Nevertheless Fig. 46



-Corrective wattless component for P.F. correction; *constant kw.*

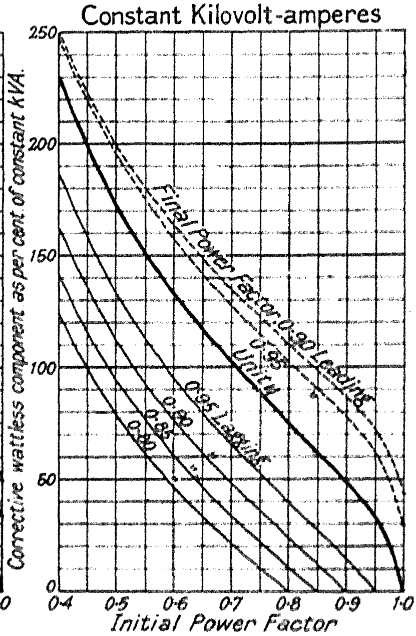


FIG. 46. Corrective wattless component for stated P.F. correction; *constant kVA.*

nds to the ultimate aim of power-factor correction in the supply network, *viz.* to increase the kW capacity (in the / A = final P.F. / initial P.F.) whilst retaining the same loading in the system. (*See* example, § 160*e*.)

vector diagrams in Figs. 41-44 are all for single-phase In the case of polyphase circuits the current (or kVA) *se* and the corrective wattless component determined from -46 is that required *per phase* in the polyphase system.

Methods of Improving P.F.—There is a number of

methods available for the production of correcting wattless kVA, the necessary amount of the correction being determined as explained in § 159. With the exception of the charging current of cables or overhead lines (§ 158) all leading wattless kVA must be produced artificially by either: (*a*) static condensers; (*b*) electro-chemical action; (*c*) synchronous motors; or (*d*) phase advancers.

(*a*) *Static Condensers.*—The static condenser consists essentially of two metal plates separated by a suitable dielectric (§ 46). For use in P.F. correction oil-immersed condensers are made in units which can be assembled in parallel to obtain the desired capacity (μF) and in series to suit the supply voltage. The condenser is connected in parallel with the load, the P.F. of which is to be corrected; the current in the condenser circuit leads 90° with regard to the E.M.F. (§ 46) and thus provides the component OC (Fig. 43.) The power consumed by the condenser is zero except for the internal losses, which do not exceed 0·5 % of the kVA rating of the condenser. The condenser capacity required, per kVA of leading wattless component to be provided, is $1\,000 / (2\pi f e^2)$ farads or $10^9 / (2\pi f e^2)$ micro-farads, where f = frequency in cycles / sec.; and e = voltage applied to the condenser. If E = voltage between 3-phase lines, $e = E$ for mesh-connected condensers; and $e = E / \sqrt{3}$ for star-connected condensers (§ 143); the mesh connection requires only one-third the condenser capacity required with star connection.* The capacity required increases as the frequency decreases, and it is rarely advisable to use condensers for P.F. improvement in systems of lower frequency than 50 cycles / sec.

Condenser units designed for pressures up to, say, 600 V each may conveniently be assembled in series for pressures up to 3 000 V. Switches may be provided so that the amount of capacity in circuit can be varied to suit the load; to obviate risk

* The voltage across the condensers is $\sqrt{3}$ times as great in the mesh as in the star connection. If the condensers be exactly proportioned to the voltage the cost of the star and mesh arrangements is practically the same, but if commercial patterns of condensers are used either the star or the mesh connection may be the cheaper. For example, if the only available standard condenser units are for 250 V and 600 V, the 600 V type would have to be used both for mesh and star connection on a 600 V system and the mesh connection would then be cheaper, but the 250 V type could be used in star on a 400 V system and would probably be cheaper than the 600 V type which would have to be used for the mesh connection.

of shock the condenser must be short-circuited through an auxiliary resistance when switched out of service. According to circumstances, it may be advisable to leave the condensers always in circuit or it may be better to switch them off with the load to which they are applied in order that no leading current may then be taken from the line. Since the capacity (μF) required for given corrective kVA varies inversely with the square of the voltage applied to the condenser it may pay to use an auto-transformer (Chapter 17) to raise the voltage at the condenser above of that the main circuit.

Standard sets of condenser units are available ranging from 172 μF to 2 760 μF at 600 V (19-312 kVA output at 50 cycles/sec.); or from $4\frac{3}{8}$ μF to 105 μF at 3 000 V (12-297 kVA output at 50 cycles/sec.); the tanks for these sets measure from $4 \times 1\frac{1}{2} \times 1\frac{1}{4}$ ft. to $6 \times 2\frac{1}{2} \times 4\frac{1}{2}$ ft., and weigh from $5\frac{1}{2}$-46 cwts. complete. For use with individual motors smaller sets of condensers are available, of capacities from 17-139 μF at 250 V, or 9-2 μF at 600 V.*

Static condensers require no special erection and no attendance or maintenance; they offer the only means of phase correction which can economically be subdivided for application to individual small loads (§ 161). If the corrective wattless component to be provided exceeds 300 kVA, it is generally cheaper and more convenient to use synchronous motors.

(*b*) *Electro-chemical Phase Advancer.*—The same effect as that produced by static condensers, *viz.* storage of energy during one half-cycle and discharge of energy during the succeeding half-cycle, can be obtained by utilising electro-chemical action instead of electrostatic capacity. If two lead grids pasted with red lead be immersed in dilute sulphuric acid and connected in an A.C. circuit they constitute a storage cell or accumulator (Chapter 18) which is 'charged' during one half-cycle and is discharged and re-charged in opposite polarity during the next half-cycle.

The amount of energy thus absorbed from and returned to the A.C. circuit is much greater than could be dealt with by a simple static condenser with equal plate area. On the other hand there are appreciable losses in the electro-chemical cell, hence the P.F. of the latter itself is relatively high. Best results appear to

* For further information the reader is referred to an instructive descriptive list issued by British Insulated and Helsby Cables, Ltd.

be obtained when the electrolyte is at about 80° C.; the resistance of the electrolyte is then low (§ 68), and the chemical activity is enhanced.

According to T. F. Wall (*Jour. I.E.E.*, Vol. 61, p. 119) the P.F. of a particular cell of this type was about 0·7 at 30° C. and 0·35 at 80° C. By connecting two cells in series in each rotor phase of a 4 h.p. induction motor the P.F. was raised from 0·5 (without phase advancer) to 0·64 (with phase advancer) on ¼-load; from 0·72-0·88 on ½-load; from 0·77-0·95 on ¾-load; and from 0·79-0·95 on full-load. Also, the efficiency of the motor between ¼ and full-load was 2 or 3 % higher with the phase advancer in use than when running with short-circuited slip rings.

(*c*) *Synchronous Motors.*—The synchronous motor (Chapter 28) is electrically identical with the synchronous alternator (§ 143) but is reversed in action, electrical energy being supplied to the stator, and mechanical energy being delivered at the shaft. In a D.C. motor the effect of varying the excitation of the field is to cause the armature speed to vary in order that the back E.M.F. may remain constant (Chapter 28). The speed of a synchronous motor is, however, fixed definitely by the frequency of supply and the number of magnetic poles (§ 135), hence the effect of varying the excitation of the field system is to cause wattless currents to flow in the stator circuit, these wattless currents being such that the resultant strength of the field remains constant notwithstanding the alteration in the exciting current. If the excitation be reduced, lagging wattless current flows in the stator circuit (from the supply system) to maintain normal magnetisation of the field system. With a higher value of D.C. excitation, no magnetising current is taken from the A.C. mains and the P.F. of the motor is unity. At yet higher values of D.C. excitation the surplus field induces (and is magnetically counterbalanced by) a *leading* wattless current in the stator circuit. In other words, an over-excited synchronous motor supplies a leading wattless current to the A.C. mains and may therefore be used, like a static condenser, to compensate for the lagging wattless current taken by other apparatus supplied from the same mains.

Over-excited synchronous motors are sometimes run light (without mechanical load) simply to effect P.F. correction and, when thus used, they are often termed 'rotary condensers.' Synchronous motors are frequently used in this way at the far end of long transmission lines in order that the latter may be relieved of wattless current which would otherwise result in

serious voltage drop (§ 155). Formerly synchronous motors were of little use for industrial power service owing to their low starting torque and the necessity of synchronising them (§ 149); now, however, there are self-synchronising motors available which start as induction motors and drop automatically into synchronism (Chapter 28); such motors can be used for P.F. correction as well as for driving a mechanical load, but their output for both these purposes is naturally lower than that in either service alone.

On practically all the present-day transmission systems, synchronous condensers of some form or other are floated on the line for the improvement of P.F. A synchronous condenser will deliver 70 % of its rated kVA in energy and approximately 70 % in wattless leading kVA for P.F. improvement. Take a case where it is necessary to raise the P.F. from 0·65-0·90, assuming a load of 450 kW. This amount of energy at 0·65 P.F. is 690 total apparent kVA, and has a component of $690^2—450^2 = 525$ wattless kVA lagging. With this same amount of energy, and the P.F. raised to 0·90 or 500 apparent kVA, the lagging component of wattless kVA is $500^2—450^2 = 220$. Now in order to raise the P.F. from 0·65-0·90 it is obvious that a synchronous condenser with a rating equivalent to the difference between 525 and 220 is required, or $525—220 = 305$ wattless kVA leading. On one system the author has in mind, this method of using synchronous condensers went too far at times, and one or more receiving stations where these units were installed had to cut out practically all the exciting current so as to reduce the voltage (W. T. Taylor, *Jour. I.E.E.*, Vol. 47, 194).

A convenient means of estimating the effect of a synchronous motor in P.F. correction and of determining the mechanical load which can be carried in addition to the correction of P.F., is illustrated by the following examples due to Van Tilburg (*loc. cit.*, § 157):—

(1) Suppose that to a load of 100 kVA, P.F. 0·8 lagging, there be added a synchronous motor carrying 35 kW useful load. The maker's data for the synchronous motor are: 50 kVA at unity P.F.; 0·9 P.F. leading at $\frac{3}{4}$-load; 0·75 P.F. leading at $\frac{1}{2}$-load; 0·4 P.F. leading at $\frac{1}{4}$-load. What is the resultant load and P.F.?

The solution is obtained from Fig. 47 which is constructed on the same principles as Fig. 42, § 157. In the diagram as reproduced the scale is 50 kVA = 1 in. The initial load of 100 kVA is represented by OI, 2 ins. long, drawn at such an angle that $OA / OI = 0·8$ (*i.e.* the initial P.F.). At full-load unity P.F. the synchronous motor (50 kVA) is represented by IB, 1 in. long, parallel to OE; and the total load is $OB = 2·88$ ins. = 144 kVA (to the scale adopted) at P.F. $= OC / OB = 2·6 / 2·88 = 0·9$ lagging. In this case the improvement is due solely to the addition of load at unity P.F.; the whole output of the synchronous motor is mechanical.

At $\frac{3}{4}$-load, the mechanical output of the synchronous motor $= \frac{3}{4} \times 50$ kVA = 37·5 kVA = $\frac{3}{4}$ in. to scale = ID in Fig. 47. As the P.F. of the machine is 0·9 leading, at this load, the total kVA of the machine = $37·5 / 0·9 = 41·6$ kVA and is represented by IE, 0·83 in. long, cutting DF at E. (*Note: DE* is drawn to the

left because the wattless component is leading.) Thus at $\frac{3}{4}$-full mechanical load on the synchronous motor, a corrective component DE is available; the total load is $OE = 125$ kVA and the P.F. is $OF / OE = 0{\cdot}94$ lagging.

The points G, H corresponding to $\frac{1}{2}$ and $\frac{1}{4}$-load are determined in the same way, and the curve BJ is sketched in.

The specified useful load of 35 kW is represented by IK ($= 35 / 50 = 0{\cdot}7$ in.). From K drop KL perpendicular to OE. Then the total load is represented by OM (line omitted for clearness) $= 2{\cdot}45$ ins. $= 122{\cdot}5$ kVA at P.F. $= OL / OM = 0{\cdot}94$.

(2) Assuming the same initial load and same synchronous motor as before, what mechanical load can the latter carry whilst improving the P.F. to 0·92?

Take any convenient length ON, erect the perpendicular NP, and mark off $OP = ON / 0{\cdot}92$; then $\cos \phi = 0{\cdot}92$. Produce OP to cut the curve BJ at Q. Draw RS through Q perpendicular to OE. Then $IS = 0{\cdot}87$ in. $= 43{\cdot}5$ kVA to scale, and this is the mechanical load which the motor could carry under the prescribed conditions.

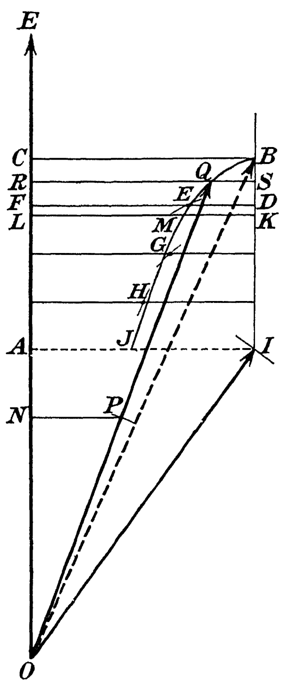
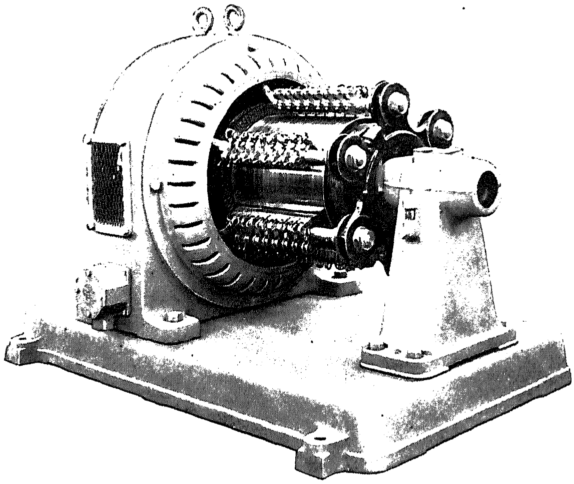


FIG. 47.—Effect of synchronous motor on P.F.

By using a regulator, on the principle of the Tirril type (§ 147), the field of a synchronous motor can be varied automatically as required to maintain predetermined P.F. in a system.

During periods of light load the spare alternators in a station may be operated as over-excited synchronous motors, their prime movers being uncoupled or, in the case of turbines, run idle *in vacuo.* The alternatoıs in service are thus relieved of wattless current, but the improvement does not extend beyond the generator bus bars; the transformers, transmission lines, etc., still operate at low P.F.

(*d*) *Phase Advancers.*—Though static condensers and synchronous motors are 'phase advancers' when used for P.F. correction, this term is generally reserved for special machines which may be connected in the rotor circuit of an induction motor to improve the P.F. of the latter. The use of such auxiliaries is only practicable in the case of large motors. The principle employed is that of injecting through the slip rings of the motor a current

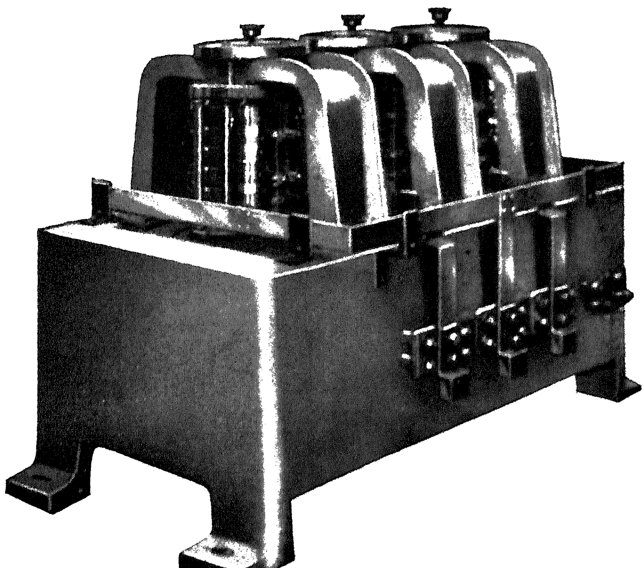


British Thomson-Houston Co., Ltd.

THREE-PHASE EXCITER (PHASE ADVANCER) FOR USE WITH AN INDUCTION MOTOR.

In its simplest form this type of phase advancer comprises an armature wound like that of a D.C. machine and an unwound stator. The armature is driven by an auxiliary motor or it may be belt-driven from or direct-coupled to the main induction motor. After starting the main motor with resistance between its slip rings, the latter are switched on to the brushes of the phase advancer. Three-phase, low-frequency slip current from the main rotor then flows to the armature of the phase advancer and establishes a rotating field. By driving the phase advancer at higher than the synchronous speed corresponding to this rotating field, the advancer can be made to supply all the magnetising current for the main motor which then operates at unity P.F. If the speed of the phase advancer be increased, the main motor supplies leading current to the network in which it is connected. Induction motors of about 40 kW have been built with a phase advancer of this type on an extension of the main motor shaft within one of the end casings of the combined set. The cost of a separate phase advancer is not likely to be justified unless the main motor is 100 kW or more, and normally operating at 0·85 or lower P.F. By varying the speed of the phase advancer unity P.F. can be maintained down to one-third rated load. If phase correction is required at lower loads the magnetisation of the main motor is best effected by D.C. and the machine then becomes a 'synchronous induction' motor. The phase advancer shown above has a capacity of 35 kVA at 770 r.p.m. It is a 4-pole machine, designed for a full-load current of 500 A, and arranged for driving by belt from the main motor. The power required to drive it is only that absorbed by friction and other losses, and is often less than the reduction effected in the losses of the main motor. The maximum torque of the latter is greatly increased by the use of the phase advancer.

[*To face p.* 236.



General Electric Co., Ltd., London.

THE KAPP PHASE ADVANCER.

This machine is essentially a small D.C. generator. The field circuit is connected to any local source of D.C. supply, while the armature is connected, through suitable control gear, to the rotor of the induction motor. When the induction motor is running and the phase advancer is in circuit with its rotor, the armature of the phase advancer oscillates in synchronism with the low frequency 'slip current' of the rotor, this alternating current causing the phase advancer to act alternately as a motor and as a generator. A back E.M.F. is thus established which is leading with regard to the normal current of the rotor, and therefore compensates for the lagging component of the induction motor alone.

[To face p. 237.

which is leading with regard to the rotor voltage. This current relieves the stator circuit of the duty of magnetising the machine and, as the leading current is supplied to the rotor at the low voltage corresponding to the 'slip' of the rotor, the kVA capacity of the phase advancer need be only 5 °/$_{o}$ (or less) of the kVA correction effected in the main supply circuit. The full corrective kVA would have to be provided if a static or rotary condenser were used in the supply circuit. The 'phase advancer' is thus at a great advantage where high-power motors are concerned.

The Scherbius method of controlling the speed and improving the P.F. of a 3-phase slip-ring motor involves the use of an auxiliary 3-phase commutator motor driving an induction generator. The stators of the main motor and of the induction generator set are connected to the bus bars, and the rotor of the main motor is connected to the commutator motor. On reducing the speed of the main motor, 'slip-energy' is transferred to the auxiliary motor, which then drives the induction generator above synchronous speed and restores energy to the bus bars. Control is by varying the excitation of the commutator motor, and thus applying a variable back E.M.F. to the rotor of the main motor. By use of a special phase transformer, the phase of the current through the auxiliary commutator motor and the rotor of the main motor can be varied, and thus the P.F. of the main machine raised to unity.

The Miles Walker phase advancer is provided with main exciting windings on the stator which permit the phase of the advancer E.M.F. to be adjusted at will. If the advancer E.M.F. acts in conjunction with the rotor E.M.F. of the main motor, the slip of the latter is reduced; the phase advancer is then actually delivering energy to the main rotor. On the other hand, if the advancer E.M.F. opposes the rotor E.M.F. the rotor slip is increased, and the advancer runs as a motor driven by energy withdrawn from the main rotor circuit; this offers a convenient and economical means of slowing down the main motor. Compensating windings on the stator of the advancer ensure good commutation. For further information *see Jour. I.E.E.*, Vol. 42, p. 599, and Vol. 50, p. 329.

The Kapp phase advancer makes use of the fact that a conductor carrying A.C. and oscillating in a D.C. field becomes the seat of a leading E.M.F. which improves the P.F. of the A.C. As applied to a 3-phase induction motor, the phase advancer consists of three bipolar D.C. armatures vertically above each other in a single main carcase. The field magnets of these armatures are connected to an exciter on the induction motor shaft. The three armatures themselves are in delta-connection, and connected to the slip rings of the induction motor. The phase advancer is short-circuited by interlocked switchgear, whilst the induction motor is being started; then the short-circuit is removed and the low-frequency rotor-slip current sets the armatures in oscillation, a leading E.M.F. is induced in them, and the P.F. of the motor is improved and the B.H.P. of the machine increased. For further information *see Electrician*, Vol. 69, pp. 222, 272; and *Jour. I.E.E.*, Vol. 51, p. 243; Vol. 61, p. 89.

The part played by compensating windings in improving the P.F. of A.C. commutator motors is mentioned briefly in Chapter 28,

and the subject is one of too specialised a nature to justify further treatment in these pages.

161. Location and Control of Apparatus for P.F. Correction.—It is clearly desirable that there should be placed immediately adjoining every load of low P.F., phase correcting apparatus which will raise the P.F. of the combination to unity, thus relieving even the feeders of wattless current. P.F. correcting apparatus relieves the generators and the circuit between itself and the generators, but *not* the circuit between itself and the load. The application of synchronous motors or phase advancers to large individual loads is economically practicable. Static condensers can be connected directly in parallel with the load and switched in and out with the latter; condensers are, however, only applicable to relatively small loads and cannot easily be adjusted to suit wide variations in load. P.F. correction for miscellaneous industrial loads is generally best effected by synchronous motors located in sub-stations. By plotting a P.F. map of the system the best situations for the corrective apparatus can be determined and the compensation can be adjusted continuously to suit the load; unless the compensation is thus adjusted there may be leading wattless currents at times, and these are as objectionable as lagging current (§ 153).

Centralised Production of Wattless Current.—Under practical conditions it is impossible to operate an A.C. system at an average power factor of unity, hence the current has inevitably a wattless component which must be produced by the generators which feed the system. It has been suggested that rather than to allow all the generators to operate at or about the mean power factor of the system it would be better to supply all the wattless current from one generator (operating at practically zero power factor), the other generators then operating at unity power factor. This method would concentrate in a single unit all the idle generating capacity and investment which are otherwise divided between all the generators on the network; and, in general, the conditions for controlling the generation of wattless current would be more favourable in a plant devoted specifically to this duty. The zero power factor generator would require little mechanical power to drive it (say 10 % of the kilovolt-ampere output at zero power factor) and this energy—representing the losses due to the wattless current—could generally be supplied more economically by a special prime mover than by a synchronous motor running light and over-excited (§ 160 *b*) for power factor correction. Again, the turbo-generator normally used to supply the wattless current could be used in emergency to supply effective power up to the kilowatt rating of the prime mover. The distribution of the wattless current from a central point would generally involve an increase in the I^2R losses in the mains, but the actual increase in these losses should not outweigh the advantages gained in other directions. It is purely a financial problem to determine the economy or otherwise of centralised wattless generation in any particular system. (*See also* § 320.)

Bearing in mind the effect of low P.F. in reducing the effective kW capacity of plant, on which depend the fixed costs per kWh (§ 272), it seems that wattless current can be produced most economically in stations where the ratio of fixed (capital) to running costs is lowest. In a transmission line the fixed costs are high compared with the cost of energy dissipated in the line, hence the long-distance transmission of wattless current, resulting in reduced kW capacity of the line, is to be avoided.

162. Economics of P.F. Correction.—The desirability of P.F. correction on technical grounds is obvious from § 155, from which it will be seen, however, that the ill effects of low P.F. are at the expense of the supplier of electricity. Unless the supply tariff penalises low P.F. (§ 274) there is no inducement to the consumer to improve the P.F. of his load. On the other hand, the supplier may be compelled to raise the P.F. of the system in order that the declared voltage may be maintained at the consumer's terminals, or he may find it cheaper to install and operate apparatus for P.F. correction than to leave idle the equipment which is rendered unproductive by low P.F., and to supply the additional losses occasioned by low P.F. This is a purely commercial problem, and must be considered for each case on its merits. In an A.C. supply system operating at 0·6 P.F. the capital charges per effective kW capacity of the generating station and distribution equipment are perhaps 50 % higher than they would be if the P.F. were unity.

The following excerpts are instructive; the costs mentioned are pre-war values, but the relative values are still about the same.

For an expenditure of 7s. or 8s. per kVA 'corrected,' it is possible to obtain the advantages of P.F. correction throughout the supply system, *i.e.* on cables, transformers, and generating plant. If that is considered for any particular system it will be found that it gives an excellent return on the investment (Larke, *Jour. I.E.E.*, Vol. 53, p. 433).

The cost of phase advancers per wattless leading kVA introduced into the line may be about 10s.; for synchronous condensers about 30s.; and for static condensers about 40s. This is very much less than the cost per kVA of the generators, transformers, and cables for generating and transmitting wattless currents (G. M. Brown, *Jour. I.E.E.*, Vol. 53, p. 662).

The installation of power-factor correcting apparatus is cheaper than increasing the plant capacity of the whole system (for the same final kW load) if the ratio: (Cost per kVA compensated by P.F. correction) / (cost per kVA for whole electrical equipment, generators, switchgear, transformers, cables, etc.) is less than $(\cos\phi_2 - \cos\phi_1) / \sin(\phi_1 - \phi_2)$. This ratio is simply the numerical increase in P.F. divided by the sine of the angle of phase advancement. It is never economical to install P.F. correcting apparatus if the above ratio exceeds $\sin\phi_1$; for

any marked economy to result the ratio should be distinctly less than sin ϕ_1 (*Power Factor Correction*, by A. E. Clayton (Pitman)).

163. **Bibliography** (see explanatory note, § 58). In addition to the papers mentioned in the preceding paragraphs there have been innumerable contributions to technical periodicals and to the proceedings of scientific bodies. At the time of writing, the only book dealing exclusively with the subject appears to be *Power Factor Correction*, by A. E. Clayton (Pitman).

CHAPTER 6.

SOURCES OF ENERGY AND PRIME MOVERS.

164. Methods of Driving Generators; Power Required.—Whether of large or small size, a generator (dynamo or alternator) may either be directly coupled to its prime mover, the two shafts being joined up by half-couplings or flexible couplings, or it may be driven by belt or rope. The cost of a generator depends so much on its speed that where low-speed prime movers are used a belt drive is generally necessary; with low-head water turbines even gearing often has to be employed. On the other hand, with high-speed prime movers direct coupling is generally adopted. In the case of steam turbines the mechanical construction of a sufficiently high-speed dynamo offers difficulties,* and special design is necessary.

The B.H.P. required to drive a given dynamo at its rated full load = (Watts / 746) × (100 / Efficiency %). For example, a generator with an output of 41 A at 220 V gives 9 000 W or 9 kW, and if the efficiency is 88 % the B.H.P. required to drive it will be (9 000 / 746) × (100 / 88) = (say) 14 B.H.P. It must be remembered, however, that all generators are capable of running for a limited time on a 25 % overload (§ 136), and this advantage will be lost if the prime mover cannot do likewise. With oil and gas engines, it is especially necessary to state the *maximum* B.H.P. which is required at the coupling or pulley under the given conditions of fuel, altitude, and so forth (§ 179).

Where a belt drive is necessary it may be noted that the maximum tension which single belting of ordinary thickness (say $\frac{1}{4}$ in.) will stand in practice is about 90 lbs. per inch of width. The H.P. transmitted is $(T - t)v / 33\,000$, where T and t are the tensions on the tight and slack sides respectively, and v is the linear velocity in ft. per min. This gives H.P. $= vb / 750$ or $b =$ H.P. $\times 750 / v$, where b is the width of single belt in inches; since 746 W = 1 H.P. the product vb represents very nearly the watts transmitted. A double belt will transmit some 60 % more. In the case of ropes the H.P. transmitted is $= Tv / 44\,000$, where T

* *See also* 'Difficulties of Design of High-speed Generators,' by A. B. Field, *Jour. I.E.E.*, 54, pp. 65 *et seq.*; also § 145 herein.

denotes (Safe working load on each rope × Number of ropes). The safe working load is about 200 lbs. per sq. in., and v may vary from 4 000 to 5 000 ft. per min.

165. Sources of Energy.—The mechanical energy required to drive dynamo-electric generators (which are the only type used for commercial supply (§§ 126, 132)) may be that already available in nature (wind or water power), or it may be derived from the heat of solar radiation or the heat of combustion of fuels. The shortage and high cost of fuel in all countries have directed attention to the more extensive development of water power (Chapters 8-10); improved types of water turbines and increased use of automatic plant (§ 187) have made profitable the development of many falls which have hitherto been regarded as useless. In Great Britain, however, coal is still the principal source of electrical energy.*

Though wind power is fickle and cannot economically be utilised in high-power units, it offers a tempting means of providing energy for small estates. In this application the wind wheel is geared to a D.C. generator which is connected in parallel with a storage battery to the supply mains. The storage battery is essential to the maintenance of supply during periods of calm. Though each case must be considered on its merits, it may be doubted whether the capital and maintenance costs of the windmill and relatively large storage battery required, do not exceed those of the self-starting petrol engine and small capacity battery (§180) which generally could be employed in its stead. Formulæ for the horse-power of wind turbines are complicated and none too reliable. It is claimed that a wheel 25 ft. in diameter develops about $2\frac{1}{4}$ kW at the generator terminals when the wind speed is $12\frac{1}{2}$ m.p.h. and 18 kW when the wind speed is 25 m.p.h.

* The subjoined data are derived from statistics published by the Electricity Commissioners :—

Year ending March 31	1921	1922
No. of stations submitting returns	501	587
Total kWh generated in millions	5167·3	4884·7
Percentage of total kWh generated from or by :—		
Coal and coke	95·9	97·22†
Waste heat	3·12	1·11
Oil engines	0·46	0·64
Destructors	0·34	0·36
Water power	0·09	0·59
Gas engines (town gas)	0·08	0·08

† 96·9 % in steam stations and 0·32 % in gas producer stations.

The power developed increases roughly with the square of the diameter of the wheel and with the cube of the wind speed. There is obvious advantage in locating the windmill on a hill-top, where there is seldom a calm and where the mean velocity of the wind is higher than in valleys. If the hill-top site is far from the prospective electrical load, the scheme cannot be developed with direct current. The use of an alternator would solve this difficulty by making high-voltage transmission practicable, but no storage of energy is economically feasible in an A.C. system. By the use of induction generators (§ 144) at the wind turbine, the latter can be situated at the most favourable site, alternating current being transmitted at high voltage from the asynchronous generator to supplement the output from synchronous generators in an existing A.C. supply system. Interesting suggestions for the use of windmills to pump sea water to the top of cliffs, the water being then delivered as required to Pelton-wheel generators at the bottom, are given by R. A. Fessenden, *Electrician*, Sept. 16, 1910.

Direct utilisation of sun heat to raise steam in large area low-pressure boilers, or in high-pressure boilers at the focus of suitable reflectors, is quite practicable in countries which are practically free from clouds. The solar radiation reaching the earth's surface has been estimated to be equivalent to 5 000 H.P. per acre at noon in summer. The Meadi (Egypt) sun absorber, erected in 1913, had a $4\frac{1}{2}:1$ ratio of mirror to boiler surface and, at 40 °/ₒ boiler efficiency, developed 63 B.H.P. per acre covered by the plant.* The Shuman engine which was used consumed 22 lbs. of steam at atmospheric pressure per B.H.P.-hr. It was estimated that this installation could compete with coal at £3 10s. a ton. The principal utility of such installations is probably in irrigation and other pumping service.

166. Efficiency of Production of Mechanical Energy by Combustion of Fuel.—Heat derived from the combustion of fuel may be used to raise steam from which mechanical energy is then derived by allowing the steam to expand in a reciprocating engine or turbine, or the fuel may be burned in the engine itself (*internal combustion*), the gases thus formed at high pressure in a confined space being then allowed to expand, and so to develop mechanical

* For details of this and other sun-absorbers *see* papers by A. S. E. Ackermann before the Soc. of Engineers, April, 1914, and the Royal Soc. of Arts, April, 1915.

energy. 'Waste heat,' such as that in the flue gases from an industrial furnace or in the exhaust gases from an internal combustion engine, can be used to raise steam for use in an auxiliary power plant.

External Combustion Cycle.—The 'mechanical equivalent' of 1 B.Th.U. (§ 48) is about 778 ft.-lbs. but it must *not* be assumed that the whole of the heat developed by the combustion of fuel can be converted to mechanical energy in this proportion. Mechanical energy can be derived from heat only when the temperature changes. If Q B.Th.U. be delivered to any heat engine at an *absolute** temperature $T_1°$ F. and exhausted at absolute temperature $T_2°$ F, the amount of heat which could theoretically be converted into mechanical energy $= Q(T_1 - T_2) / T_1$ and the thermal efficiency would then be $(T_1 - T_2) / T_1$. This shows at once that the thermal efficiency is higher, the greater the range of temperature $(T_1 - T_2)$ in the working cycle.

From steam tables it will be found that the absolute temperature of saturated steam at 165 lbs. / sq. ins. (absolute) is 825° F., and at 1 lb. / sq. in. (about 28 ins. vacuum) is 561° F., hence the theoretical thermal efficiency of an engine working between these limits is (825 − 561) / 825 = 32 °/₀. Allowing for the losses inevitable in an actual engine the thermal efficiency might be 20 °/₀, and the engine would then have a *relative efficiency*, compared with the ideal engine, of 20 / 32 = 0·62 or 62 °/₀.

The *mechanical efficiency* of the engine, which bears no relation to either the actual or the relative thermal efficiency, is the ratio of the mechanical energy available at the shaft to that developed at the point where the heat is converted to mechanical energy. In a reciprocating engine the mechanical efficiency = Brake-H.P. / Indicated-H.P., and the difference (I.H.P. − B.H.P.) = the frictional loss in the engine plus the power required to drive the air pump (in condensing engines). The mechanical efficiency may be 90-95 °/₀ in single-cylinder non-condensing engines, and 75-85 °/₀ in condensing engines.

The total heat of saturated steam at, say, 165 lbs. / sq. ins. absolute is 1 195 B.Th.U. / lb. (reckoned above 32° F., *see* steam tables), and that of standard steam at $\frac{1}{4}$ lb. / sq. in. (about $29\frac{1}{2}$ ins. vacuum) is 1 086 B.Th.U. / lb. Under actual conditions about 1 000 B.Th.U. / lb. of steam consumed is rejected in the condensing water or, in a non-condensing plant, lost to the atmosphere. This loss represents about 60°/₀ of the heat value of the coal burned below the boilers. The amount of heat thus rejected

* The *absolute* temperature in Fahrenheit degrees = (temperature on the Fahrenheit scale + 459); the absolute zero of temperature being − 459° F., *i.e.* 459 + 32 = 491° F. below the freezing-point of water.

could only be reduced by lowering the final temperature of the steam; 100 % thermal efficiency in any heat engine is not even theoretically possible unless the working fluid can be utilised down to the absolute zero of temperature (– 273° C. or – 459° F.). In practice the lower limit of temperature is 212° F. for a steam engine exhausting to atmosphere, and from 80°-120° F. for a condensing engine, according to the vaccuum maintained.

The lower limit of temperature for the steam cycle being thus fixed, the only means of increasing the efficiency of the cycle itself (as distinct from reducing the heat losses in the boiler and pipe line, and the friction losses, etc., in the engine) is by raising the upper limit of temperature. This may be done by using higher steam pressures and by superheating the steam to the highest temperature permitted by mechanical considerations (§§ 172, 174).

The use of mercury vapour in a thermo-dynamic cycle offers a means of raising the upper working temperature (and thus increasing the possible efficiency ($T_1 - T_2 / T_1$) without employing high pressures.* The first commercial installation operating on this principle is at the Dutch Point station of the Hartford (Conn.) Electric Light Co.† and has an oil-fired mercury boiler containing 30 000 lbs. of mercury. On top of this is a 2 000 kVA mercury turbo-generator, the exhaust mercury vapour from which is condensed by the water tubes of a boiler which supplies steam to steam turbines as usual. In such a plant mercury vapour can be sent straight from the mercury boiler to the condenser boiler if desired. The mercury boiler and turbine can be added to existing steam plants without affecting the steam cycle; the mercury transfers heat from the fuel to the steam and the additional power, derived from the mercury cycle, is expected to halve the overall fuel con-consumption per kWh.

The advantages of mercury as a thermo-dynamic fluid are: (1) Its boiling-points at desired pressures are convenient (about 732° F. at 25 lbs. absolute, 677° F. at atmospheric pressure, and 457° F. at 28 ins. vacuum), thus making possible operation in a range of temperature above that of the usual steam cycle without much exceeding atmospheric pressure. (2) Its high specific gravity (13·6) makes possible gravity feed, gravity sealing of valve stems, etc., and centrifugal sealing of turbine packings. (3) At the temperatures used, mercury is neutral to air, water, iron, and such organic substances as it may come into contact with. (4) The interior of a mercury boiler is always perfectly clean. (5) The vapour density of

* The pressure of steam rises rapidly with temperature, and the turbine is not well adapted for utilising very high pressures.

† See *El. Wld.*, Vol. 79, p. 1 186.

mercury is so high that the spouting velocity is low and a very simple type of turbine can be used, generally a single wheel. (6) It is expected that there will be no erosion of the turbine blades, these not being wetted. (7) The volume of the vapour at convenient condensing temperatures is such that the turbine buckets need not be abnormally high (this is one of the chief difficulties in steam turbine design). (8) The mercury condensing boiler is very small and simple compared with a fuel-heated boiler; it resembles a surface condenser and is immune from scaling and burning.

The cost of mercury is high but only a relatively small quantity is required; the vapour is very poisonous, but the system can be sealed effectively (W. L. R. Emmet, *Gen. El. Rev.*, Vol. 17, pp. 47, 99).

Internal Combustion Cycle.—The inherent advantages of the internal combustion cycle are that: (1) Heat is developed in the actual space where the development of mechanical energy occurs, thus eliminating boiler and pipe losses. (2) The temperature range of the working cycle (and therefore the thermal efficiency attainable) in the engine is greater than that of the steam cycle.

167. Thermal Efficiencies of Prime Movers; Fuel and Steam Consumptions.—A knowledge of the approximate thermal efficiency of various prime movers is useful in practice, because it enables one speedily to form a good idea of the amount of any particular fuel consumed by a particular type of engine. The heat-equivalent of mechanical work is about 42·4 B.Th.U. per H.P.-min., or 2 545 B.Th.U. per H.P.-hr., so that if the thermal efficiency of an engine be E °/ₒ, that engine will require ($2\,545 \times 100 / E$) B.Th.U. per B.H.P.-hr., and if the calorific value of the fuel used be H B.Th.U. per lb., the fuel consumption of the engine will be ($254\,500 / E \times H$) lbs. per B.H.P.-hr. If the heat of the fuel is developed in a boiler or gas producer before passing to the engine, the fuel consumption of the engine will be given by ($25\,450\,000 / E \times H \times e$), where e is the thermal efficiency of the boiler or producer, etc. This method of evaluating fuel consumption is applied in Table 15, the results in which are in good general agreement with the practical data given later. Since, however, a fractional difference in fuel consumption represents a large sum of money per annum where the production of large quantities of energy is concerned (§ 193), it is necessary to attach great importance to such differences, in practice, and this involves taking into account small differences in calorific value, degree of superheat, vaccuum, barometric height, and so forth. Since all these factors cannot be taken into consideration in such a summary as Table 15 the data there given are correspondingly approximate. Values of

TABLE 15.—*Thermal Efficiency of Prime Movers, with derived Fuel Consumption Data.* (*See also Table* 20, § 179.)

Prime Mover.	Fraction of Full Load.	Thermal Efficiency. Engine (from Admission to Crank-Shaft).	Boiler or Producer, etc.	Overall (Fuel to Crank-Shaft).	B.Th.U. per B.H.P.-hr.	Fuel Used and Calorific Value: (*a*) per Lb. (*b*) per C. Ft.	Fuel Consumption per B.H.P.-hr.* (on Load Stated in Col. 2).
Steam engines—		%	%	%	B.Th.U.		
Simple	1	10 to	70	7	36 400		2·7 lbs.
		15	80	12	21 200		1·6
Compound (condensing, saturated steam)	1	16 to	75	12	21 200	Average Coal	1·6
		18	80	14·4	17 700	13 500 (*a*)	1·3
Triple or quad. exp. (saturated or superheated)	1	20 to	75	15	17 000		1·25
		24	80	19·2	13 250		0·98
Steam turbines—							
Up to 500 kW . .	1	10 to	70	7	36 400		2·7 lbs.
		15	80	12	21 200		1·6
5 000 to 10 000 kW .	1	20 to	75	15	17 000	Average Coal	1·25
		23	80	18·4	13 850	13 500 (*a*)	1·03
Exceptional . . .	1	26 to	75	19·5	13 000		0·96
		28	83	23·3	10 900		0·81
Heavy oil engines (including Diesel)	1	25 to	—	25	10 200	Crude oil	0·55 lb.
		30 or	—	30	8 500	18 500 (*a*)	0·46
		35	—	35	7 275		0·39
Paraffin engines—							
Small	1	15 to	—	15	17 000	Paraffin	0·87 lb. (or pint
		20	—	20	12 700	19 500 (*a*)	0·65 approx.)
Large	1	20 to	—	20	12 700		0·65
		25	—	25	10 200		0·52
							Lb. Pint.
Petrol engines . . .	1	16 to	—	16	15 900	Petrol	0·8 0·92
		24	—	24	10 600	20 000 (*a*)	0·53 0·61
Gas engines—							Lbs. Coal. C. Ft. Gas.
Using producer gas . .	1	20 to	75	15	17 000	Anthracite or	1·22 94 †
		25	85	21·3	11 950	bituminous coal	0·85 76 †
	¾	20 to	75	15	17 000	14 000 (*a*)	1·22 94 †
		23	85	19·6	13 000	yielding suction	0·93 82 †
	½	15 to	70	10·5	24 200	or producer gas	1·73 126 †
		20	80	16	15 900	135 (*b*)	1·14 94 †

* It must be understood that the figures in this column are *calculated* (as explained in text). The basis on which they are calculated is rational, so that the figures are a reliable indication of the results which may be expected in practice. At the same time, it is impossible to lay down hard and fast rules. For instance, in steam plant, the design of engine, pattern of boiler, quality of coal, draught, skill of stoker, or good working of the mechanical stoker, all affect fuel economy to a marked degree.

Assuming 94 % efficiency in large generators at full-load, add 43 % (i.e. multiply by 1·43) to those figures in this column which refer to operation at full-load in order to obtain the fuel consumption per kWh delivered by the generator on full-load.

† These figures are naturally referred to the thermal efficiency of the engine *alone*.

TABLE 15 (*continued*).

Prime Mover.	Fraction of Full Load.	Thermal Efficiency. Engine (from Admission to Crank-Shaft).	Thermal Efficiency. Boiler or Producer, etc.	Thermal Efficiency. Overall (Fuel to Crank-Shaft).	B.Th.U. per B.H.P.-hr.	Fuel Used and Calorific Value : (*a*) per Lb. (*b*) per C. Ft.	Fuel Consumption per B.H.P.-hr.* (on Load Stated in Col. 2).
		%		%	B.Th.U.		
Gas engines—							
Using town gas . .	1	20 to 25	Thermal efficiency of gas-making plant does not concern the engine-user in these cases.	20	12 700	Town (or lighting gas) 500 (*b*)	25·4 c. ft.
				25	10 200		20·5
	¾	20 to 23		20	12 700		25·4
				23	11 100		22·2
	½	15 to 20		15	17 000		34·0
				20	12 700		25·4
Using coke-oven gas .	1	20 to 25		20	12 700	Coke-oven gas 430 (*b*)	29·5 c. ft.
				25	10 200		23·7
	¾	20 to 23		20	12 700		29·5
				23	11 100		25·8
	½	15 to 20		15	17 000		39·5
				20	12 700		29·5
Using blast-furnace gas .	1	20 to 25		20	12 700	Blast-furnace gas 90 (*b*)	141 c. ft.
				25	10 200		114
	¾	20 to 23		20	12 700		141
				23	11 100		124
	½	15 to 20		15	17 000		190
				20	12 700		141
Exceptional . . .	1	25 to 30		25	10 200	Natural gas 800-850 (*b*)	12·5 c. ft.
				30	8 500		10·4

fuel and steam consumption taken from practice are given in the later paragraphs dealing with individual types of prime movers.

The economy of steam engines and turbines is generally expressed in terms of steam consumption either per I.H.P.-hr., per B.H.P.-hr. (or particularly in generator sets) per kWh. If *a* be the percentage mechanical efficiency of the engine and *b* the percentage efficiency of the electric generator :—

	Lbs. per I.H.P.-hr.	Lbs. per B.H.P.-hr.	Lbs. per E.H.P.-hr.	Lbs. per kWh.
W lbs. per I.H.P.-hr. =	W	100 W / *a*	10 000 W / *a*.*b*	13 400 W / *a*.*b*
W lbs. per B.H.P.-hr. =	*a*.W / 100	W	100 W / *b*	134 W / *b*
W lbs. per E.H.P.-hr. =	*a*.*b*.W / 10 000	*b*.W / 100	W	1·34 W
W lbs. per kWh =	*a*.*b*.W / 13 400	*b*.W / 134	0·746 W	W

The value of *a* for good steam engines is from 75 to 85 % for condensing engines (§ 166); 80 % would be a reasonable average. The corresponding figure for Diesel engines is lower;

it may be 84 or 85 °/₀ so far as concerns the motor itself, but, allowing for power required to drive the air compressor, the net B.H.P. averages from 70-77 °/₀ of the I.H.P. in high- and low-speed four-cycle engines respectively, and from 67½-71 °/₀ in high- and low-speed two-cycle engines. The term indicated horse-power has no meaning in connection with a steam turbine, and the nearest approach we can make to a factor corresponding to *a* above is to say that the mechanical output of a turbine is from 70-75 °/₀ of the mechanical equivalent of the heat drop (as reckoned according to the equation for adiabatic expansion). Suitable averages for the generator efficiency *b* are 94 °/₀ in large machines, 90 °/₀ in 100 kW machines, and 85 °/₀ in 10 kW generators.

Fuel consumption data relating to steam engines and turbines, and based on considerations of thermal efficiency, are included in Table 15, but these figures must *not* be converted to steam consumption data simply by multiplying the (lbs. of fuel per B.H.P.) by the (evaporation per lb. of coal); *see* Table 17, § 170. To do this would give an incorrect result, since the evaporation data in Table 17 are referred to 212° F. The heat required to evaporate 1 lb. of water from and at 382° F. (the temperature corresponding to 200 lbs. absolute steam pressure) is 12½ °/₀ less than is required to evaporate the same weight at 212° F.; where steam is superheated, the heat required for the latter purpose compensates to some extent the decrease in latent heat of evaporation, with rising temperature. Due to the varying heat content of 1 lb. of steam under different conditions, statement of the steam consumption of an engine gives no definite measure of the thermal efficiency of the latter unless the steam conditions be specified fully. It is much better to state the heat consumption per I.H.P.-min. or per B.H.P.-min. Theoretically I.H.P. - min. = 33 000 / 778 = 42·4 B.Th.U. If the actual heat consumption (measured at the stop valve) be *h* B.Th.U. per B.H.P.-min., the thermal efficiency of the engine is 4 240 / *h* °/₀. (*See also* § 191.)

168. Fuels for Steam Boilers.—By far the greatest part of the electrical energy produced in Great Britain is derived from the combustion of coal, sometimes with the admixture of coke (§ 165). Generally these fuels are burned below steam boilers but, in relatively small installations, they can be used to advantage in gas producers (§§ 178, 181).

Coal Purchase and Storage.—Coal is frequently purchased under a contract which fixes a basic price for coal of stated calorific value (say, 12 000 B.Th.U. / lb.). A proportionate addition to or deduction from the basic price is made according as the actual calorific value exceeds or falls below the agreed standard. Also the basic price may be modified according to the percentage of ash, moisture, and smalls in the delivered coal. For example it may be agreed to pay 2d. a ton extra for every 1 °/₀ by which the ash content falls below 12 °/₀; to deduct 1 °/₀ from the chargeable weight of coal for every 1 °/₀ by which the moisture content exceeds 10 °/₀; and to deduct $\frac{1}{4}$ °/₀ from the chargeable weight of coal for every 1 °/₀ by which the percentage of 'smalls' (passing through a $\frac{3}{8}$ in. mesh) exceeds 20 °/₀.

It is usual to store not less than one month's supply of coal in the immediate neighbourhood of the power station. This frequently involves the storage of some tens of thousands of tons. To reduce breakage and the risk of spontaneous ignition, coal stacks should not be higher than 10 or 12 ft. Dust, slack, and mixtures of coals are particularly liable to ignition. Oily waste and similar material should be excluded, and the stack should not be near hot pipes, etc. Coal may be stored satisfactorily to a depth of 20 or 30 ft. in concrete basins filled with water, but the wet coal should be drained before use. However stored, coal gradually disintegrates and loses somewhat in calorific value but the deterioration is not serious under reasonable conditions.

The use of *pulverised coal*—ground so finely that 85 °/₀ will pass through a screen with 200 meshes to the inch and 95 °/₀ through a 100-mesh screen—is claimed to make possible the efficient use of inferior material, and also to permit the solid fuel to be burned (like gas or oil fuel) with little more than the weight of air theoretically required for the process. Boiler efficiencies of 85 °/₀ and higher have been obtained during tests with pulverised coal, and the latter is as flexible to control as gas or oil. The best method of preventing atmospheric pollution by ash and boiler fouling by slag, is probably to catch the ash and slag in a sump below a sudden turn in the path of the products of combustion (on the principle of the steam separator). The cost and risk of drying, storing, and distributing the pulverised fuel are reduced by the use of pulverisers which grind the fuel at each boiler as it is required for use, but there are obvious counter-objections to such subdivision of the pulverising plant.

A mixture of oil fuel with coal ground so finely as to remain in colloidal suspension is claimed to be safer and more economical than either ingredient alone.

Coke, when dry, consists of 80-95 °/₀ carbon, the remainder being ash and 1 °/₀ or so of sulphur. Good coke with only 5 °/₀ moisture and 10 °/₀ ash is worth about 12 500 B.Th.U. / lb. and is excellent for steam raising. Unfortunately, coke readily absorbs as much as 20 °/₀ moisture.

Lignite or brown coal is used for steam raising in some countries and ranges from 6 000 to 12 000 B.Th.U./lb., an average value being 7 500 B.Th.U./lb. Many attempts have been made to utilise *peat* profitably;* the principal difficulty is that of drying the raw fuel economically (peat as dug may contain 80 % of water). The calorific value of dry peat is about 9 000-10 000 B.Th.U./lb.; and of that with 25 % water, 7 000 B.Th.U./lb. It is not necessary to dry the fuel so thoroughly for use in a gas producer as for burning below boilers, but it is prohibitively costly to transport the bulky, moist, and low-grade fuel for any considerable distance; the power plant must therefore be situated at or near the peat deposits.

Wood, sawdust, cane trash, rice husk and other similar materials may be used profitably where available. Provided that larger grate area is provided the same steaming capacity can be maintained as with coal notwithstanding the low calorific value of the fuel which may be anything from 6 000-2 000 B.Th.U/lb. *Town refuse* varies greatly in composition, but is generally worth from 1 000-2 000 B.Th.U./lb. and is profitably utilised in many places.

Oil fuel is technically excellent for steam boilers, but its cost is high and unstable. Crude petroleum has a calorific value of 18 000-19 000 B.Th.U./lb. The oil is atomised by a steam or air blast or by being forced under pressure through suitable nozzles; the rate and conditions of combustion are under immediate control, a very small surplus of air is required for complete combustion, and there is no ash formed. A boiler efficiency of 85 % or higher can be maintained, and the steaming capacity of a given boiler is about 15 % higher with oil than with coal, if baffles be provided to act as high-temperature radiating surface in place of the incandescent fuel bed. As an approximate guide, it seldom pays to use oil for steam raising if its cost per ton exceeds $1\frac{1}{2}$-$1\frac{3}{4}$ times that of the alternative coal.

Waste gases from blast furnaces, coke ovens, and steel works are used successfully in many large power plants, the gas being fed to burners below standard coal-burning types of boilers, or used in a Bonecourt boiler (§ 170).

In selecting the fuel for use in any power plant, security of

* Reports on the subject are issued from time to time by H.M. Stationery Office for the Fuel Research Board; *see also El. Rev.*, Vol. 90, p. 477.

supply is a primary consideration. The calorific value of the fuel is of less importance than the cost per 1 000 B.Th.U. developed, allowing for the cost of furnace operation and maintenance (including ash removal).

169. Recovery of By-products from Coal.—It is now generally realised that the tar, oils, ammonium sulphate, and other by-products which can be recovered from coal by a suitable process of distillation have a market value comparable with the cost of the coal itself. Though most coal is still burned in the raw state this process involves the irreparable loss of by-products which should constitute a national asset, and which are either of no value as fuel or (as in the case of benzol) would be of greater value as fuel for internal combustion engines than as boiler fuel. The ideal practice would be to subject all coal to fractional distillation, and to use each product in the application for which it was most valuable.

Theoretically, about 112 lbs. of ammonium sulphate is recoverable per ton of coal containing 1·3 % nitrogen. Actually, 15–25 lbs. is recoverable in high-temperature coke ovens and 30 lbs. or so in low-temperature plant. About 90 lbs. of tar is recoverable, and, say, 12 000 cu. ft. of coal gas and nearly 1 500 lbs. of coke are produced.

TABLE 16.—*Power Generation with and without By-Product Recovery.*

Scheme.	Total Capital Cost per B.H.P.	By Sale of By-Products per B.H.P.-hr.	Running Costs per B.H.P.-hr. Gross.	Net.
	£	d.	d.	d.
Coal-fired boilers and condensing steam engines	7·90	Nil	0·21	0·21
Pressure producers (non-recovery) and gas engines	9·10	Nil	0·18	0·18
Mond recovery plant, gas engines, and exhaust boilers	11·00	0·09	0·23	0·14
Ordinary recovery plant, ordinary gas-fired boilers, and condensing steam engines *.	16·50	0·236	0·47	0·234
Self-steaming high-recovery plant, high-efficiency gas-fired boilers, and condensing steam engines	13·00	0·125	0·292	0·167

* Price includes extra boilers to supply gas producers and to make up for low efficiency of ordinary boilers when gas-fired.

Table 16 is based on estimates by T. R. Wollaston (*Engineer*, Vol. 119, p. 326), and shows clearly the economy of power generation with by-product recovery. The data relate to alternative schemes for producing 1 500 B.H.P. (mechanical power), working 7 000 hrs. per annum at an average load of 1 000 H.P., *i.e.* at 53 % load factor; the costs given are on a pre-war basis, but this does not affect the general purpose of the comparison.

For further information the reader may be referred to a report by Sir Dugald Clerk and Professors A. Smithells and J. W. Cobb on the Coal Gas and Electrical Supply Industries of the United Kingdom, addressed to the Institution of Gas Engineers (*see also Jour. I.E.E.*, Vol. 58, p. 765); and to the publications of the Fuel Research Board (H.M. Stationery Office).

170. Steam Boilers.—Large modern boilers have up to 60 sq. ft. of heating surface per sq. ft. of grate area, and up to 6 or 8 lbs. of water are evaporated per sq. ft. of heating surface per hr. In boilers of older design the ratio of heating to grate surface is from 20 to 30 : 1, and the evaporation only 3-4 lbs. per sq. ft. of heating surface per hr. (*see also* Table 17). Values for the heating surface required in coal-fired boilers per I.H.P. of various types of engines served are as follows: Simple high-pressure, non-condensing engines, 7-8 sq. ft.; compound, non-condensing, 5-6 sq. ft.; compound, condensing, 4-5 sq. ft.; triple-expansion, non-condensing, 4-5 sq. ft.; triple expansion, condensing $2\frac{1}{2}$-3 sq. ft.; turbines, 2-$2\frac{1}{2}$ sq. ft. The weight of coal burnt per sq. ft. of grate surface per hr. depends primarily on the draught employed; the figures given in Table 17 refer to natural draught. Using forced draught, 100 lbs. or more of coal can be

TABLE 17.—*Average Boiler Data.*

Type of Boiler.	Heating Surface : Grate Area.	Evaporation per Sq. Ft. Heating Surface per Hour.	Coal per Sq. Ft. Grate per Hour.	Water Evaporated per Lb. of Coal Burned.
		lbs.	lbs.	lbs.
Cornish	20 to 30 : 1	3 to 4	15	$7\frac{1}{2}$
Lancashire	20 ,, 25 : 1	4 ,, 6	15 to 20	$7\frac{1}{2}$ to 8
Water-tube, ordinary . .	40 ,, 60 : 1	$3\frac{1}{2}$,, $4\frac{1}{2}$	15 ,, 25	$6\frac{1}{2}$,, $8\frac{1}{2}$
,, high-power * .	25 ,, 30 : 1	$5\frac{1}{2}$,, 8	25	$7\frac{1}{2}$,, 10
Bonecourt (gas-fired) . .	No grate	15 ,, 35	—	—

* *I.e.* specially compact boilers with high steaming capacity; every provision made to secure brisk circulation and rapid heat transference.

burned per sq. ft. of grate per hr., but 25-30 lbs. repres the maximum for central station practice,* and 15-20 ll usual value.

Water-tube boilers, which are at present the standa ment for steam raising in large stations—especially the & Wilcox and the Stirling types—evaporate up to 1(150 000 lbs. of water per hr. (150 000-200 000 lbs. / hr. periods), the steam pressure being up to 350 lbs. / sq. the total steam temperature (including superheat) up t Several such boilers may be required to feed a single Particulars of very high power, water-tube boiler practi be found in the *El. Rev.*, Vol. 75, p. 290.

Under ordinary conditions and with good coal, a $8\frac{1}{2}$ lbs. of water can be evaporated (from and at 212° F of coal burnt in modern boilers, rising to 9 or 10 lbs. efficiency plant skilfully operated. Coal of calorific 13 500 B.Th.U. per lb. would evaporate about 14 lbs. from and at 212° F., were it possible to use all the heat coal. Actually, the thermal efficiency of a coal-fired boile siderably below 100 %. The proper basis of comparison different boiler installations is the overall efficiency o superheater, and economiser. With a clean boiler and g the overall efficiency of boiler, superheater, and economi be 85 %, but the distribution of the heat derived from th generally within the following limits: In boiler 58 %, sup 9 %, and economiser 8 % (*i.e.* 75 % of the heat is delivere steam, falling to 55 or 60 % in inefficient installations †) flue gases 15 % (sometimes 30 %), by radiation 5 % (ofter and by moisture, unburnt residue, etc., 5 % (total loss 25 % to 40 % or more in inefficient installations). Some of t temperature heat in the gases leaving the economiser may to pre-heat the air for the furnace to, say, 195° F., the temp of the gases leaving the pre-heater being then about 300°

The Bonecourt boiler with feed heater attains an efficiency of 90-$92\frac{1}{2}$ %. This boiler is of the fire-tube ty refractory brick or twisted iron filling inside the tubes.

* The heat developed per hr. per sq. ft. of grate area is then about B.Th.U. using coal worth 11 700 B.Th.U. / lb.

† *See* 'Average Figures for the Performance of Different Types o Boilers,' by D. Brownlie, *Engineering*, Dec. 10 and 17, 1920.

or gaseous fuel or waste heat from furnaces, gas engines, etc., is used; with liquid or gaseous fuel combustion proceeds flamelessly, and in all cases the gases in the tubes impinge again and again on the heating surface, the filling material in the tubes meanwhile giving out a high percentage of radiant heat. Only 5 or 10 °/₀ of excess air is required for perfect combustion, and the evaporation is from 15-35 lbs. / sq. ft. of heating surface / hr., from and at 212° F. (Table 17). A Bonecourt boiler 6 ft. dia. × 18½ ft. long is capable of delivering 20 000 lbs. of steam per hr.*

171. Boiler Room Efficiency.—The minimum equipment and procedure required to determine and maintain efficiency in the boiler room is as follows: Coal-weighing apparatus and periodic determinations of the calorific value of the coal are required to make possible calculation of the heat input. Steam meters record the quantity, and pressure gauges and thermometers show the condition of the steam delivered; thence the thermal output of the boiler can be determined by reference to steam tables. For the complete control of the conditions of combustion, and to detect air leakage through the boiler setting, irregular fire bed, etc., manometers and thermometers (both distant-indicating) are required at various points in the path of the air and flue gases. Thermometers should be placed also inside the inlet and outlet of the superheater and economiser.

Flue gas analysis is an excellent guide to the conditions of combustion and should preferably be effected by an automatic recording apparatus which determines both the carbon dioxide and the oxygen in the gases. The ideal percentage of carbon dioxide in flue gases from a boiler burning average English coal is 18-19 °/₀; the actual percentage under good conditions and steady high load is 12-14 °/₀, but the average during 24 hrs. is rarely over 10 °/₀, and is often 8 °/₀, 6 °/₀, or less. The theoretical percentage of carbon dioxide should be approached very closely where oil or gas fuel is employed.

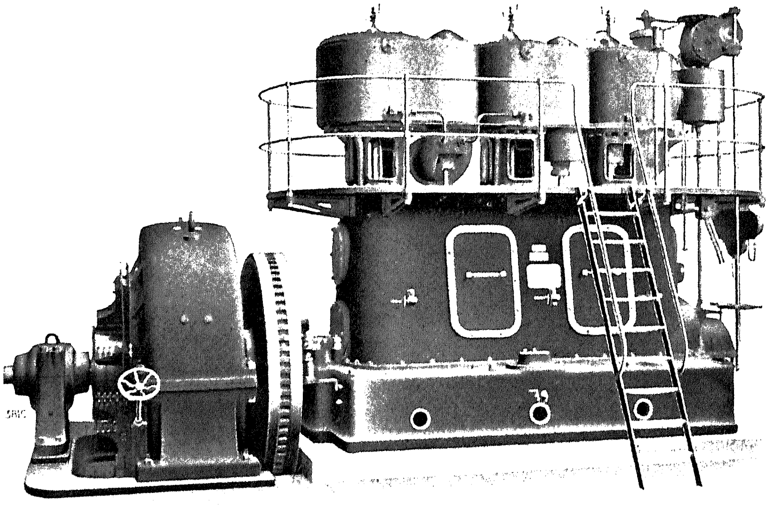
It is very important that the steam pipes, etc., be adequately lagged with heat insulating material; the loss by radiation should then be about ¼ or ⅓ B.Th.U. / sq. ft. / hr. / 1° F. temperature difference between the steam and the surrounding atmosphere

* *See also* 'Recent Development in Gas-Firing Steam Boilers,' by W. Gregson, *Proc. S. Wales Inst. Eng.*, Vol. 36, p. 279.

(compared with 3 or 4 B.Th.U. in the case of bare pipe). Inferior lagging may be worse than useless in that it simply increases the radiating surface.

The efficiency of a boiler plant is improved materially by the use of feed water which does not form scale. In condensing installations a relatively small amount of make-up feed water is required, and if this be subjected to preliminary distillation in a steam-heated evaporator no scale-making material is carried into the boilers. The steam and water circuits can be arranged so that the net expenditure of heat involved by the preliminary evaporation is very small. The feed water should nowhere be exposed to air because air in solution promotes corrosion of the boilers. The testing of feed water by its electrical conductivity is mentioned in § 119.

172. Reciprocating Steam Engines. The advantages of reciprocating steam engines compared with other prime movers where the output required is less than, say, 1 000 kW are discussed in § 189. The steam consumption of these engines varies over a wide range. Non-condensing simple engines may consume from 45-60 lbs. steam per B.H.P.-hr. in small sizes and 28-33 lbs. in 100 H.P. or larger units. The same engines worked condensing will consume, roughly, 25 % less steam or, say, 35-40 lbs. per B.H.P.-hr. in small sizes and 20-25 lbs. in larger engines. Compound, condensing engines may consume as much as 20-25 lbs. steam per B.H.P.-hr., but 15-17 lbs. is a satisfactory range where engines of 200-500 H.P. are concerned. In high-class triple-expansion engines, operating under favourable circumstances, the steam consumption is reduced to 12-14 lbs. per B.H.P.-hr. Sulzer and Allis triple-expansion engines, representing the best practice of the Continent and the United States, have a consumption varying from 11½-12½ lbs. per I.H.P.-hr., and exceptional results as low as 10 lbs. per I.H.P.-hr. (say, 10½ lbs. per B.H.P.-hr.) have been reached. At loads above or below normal full load, these consumption figures are exceeded, usually by not more than 5 % at 1¼ and ¾-full load, but by 15-20 % or more at ½-load. In '*uniflow*' *engines* the exhaust port is at the middle of the cylinder, and is opened and closed by the piston moving over it; by eliminating the passage of live steam over surfaces cooled by exhaust steam, this arrangement reduces condensation losses and improves efficiency. A certain 400 H.P.

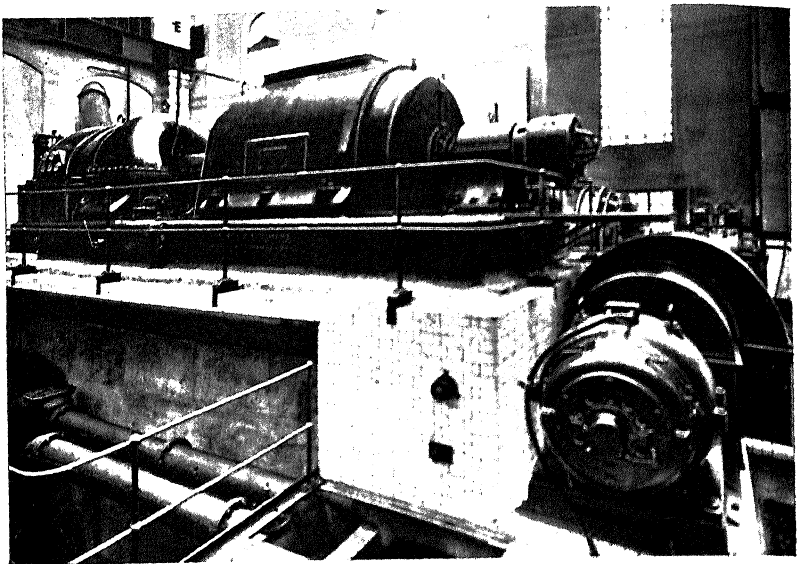


Belliss & Morcom, Ltd.

HIGH-SPEED TRIPLE-EXPANSION STEAM ENGINE DRIVING A D.C. GENERATOR.

The distinctive features are the total enclosure of working parts, and the use of forced lubrication on the arterial principle. Oil is circulated automatically to all the bearings by a pump discharging at 10-20 lbs. / sq. in. Governing is by throttle at light loads, by variable expansion at heavy loads, and by a combination of these methods at intermediate loads. Two-crank compound and non-compound engines are supplied for maximum outputs from 38 B.H.P. at 650 r.p.m. to 720 B.P.H. at 300 r.p.m. The non-compound engines are for steam pressures of 80-90 lbs. / sq. in., and a pressure of 140-150 lbs. is recommended for the compound engines. Triple-expansion engines are supplied for outputs from 260 B.H.P. at 500 / 550 r.p.m. to 2 500 B.P.H. at $187\frac{1}{2}$ / 200 r.p.m., and a steam pressure of 170-200 lbs. / sq. in. is recommended. Where the steam pressure is sufficient and the engine is to operate condensing, the triple-expansion type is best, but the compound type is often preferable for non-condensing or for working against a back pressure. The weight of the compound and triple-expansion engines respectively is roughly $\frac{5}{8}$ cwt. and $\frac{3}{4}$ cwt. per B.H.P.; or 1 cwt. and $1\frac{1}{4}$ cwts. per B.H.P., including D.C. generator and bed plate.

[*To face p.* 256.



General Electric Co., Ltd. (London).

TYPICAL TURBO ALTERNATOR SET WITH EXTERNAL VENTILATING FAN.

The set illustrated is rated at 12 500 kVA, 6 600 V, 50 cycles, 3000 r.p.m. Steam pressure 190 lbs. / sq. in., temperature 584° F. Vacuum 27½ ins. at 30 ins. barometer. Steam consumption not available at time of going to press. The approximate weight of the turbine is 60 tons and of the alternator 55½ tons. The approximate dimensions of the complete set are: Length 32 ft. 7 ins.; height 8 ft. 4 ins.; width 10 ft. 8 ins. The rotor of the generator is a solid steel forging, and the end-windings of the stator are specially supported to withstand short-circuit stresses.

[*To face p.* 257.

simple, condensing engine of this type consumed about 12 lbs. steam per B.H.P.-hr.*

The advantage of superheating steam for use in reciprocating engines is theoretically very small but is actually very great; there is a small increase in the theoretical efficiency of the cycle where superheated steam is used, but the great advantage lies in the more or less complete elimination of cylinder condensation. In typical cases from 10 to 25 °/。 reduction in coal consumption is effected by the use of superheated steam in reciprocating engines (*see also* § 174).

The enormous increase in specific volume of steam at low pressures makes it difficult to utilise high vacua as effectively in reciprocating engines as in turbines.

In Germany, W. Schmidt has experimented for many years with the use of pressures up to 900 lbs. / sq. in. in reciprocating engines (*Science Abstracts*, Vol. 25, p. 2). The steam is superheated between the high and low-pressure cylinders, and it is claimed that the heat consumption is as low as 146 B.Th.U. / B.H.P.-min., corresponding to 29 °/。 thermal efficiency. Ordinary compound condensing engines using steam at 120-180 lbs. / sq. in., superheated to 250° C., commonly require 200-250 B.Th.U. / I.H.P.-min. or, say, 250-300 B.Th.U. / B.H.P.-min. It is claimed that the high-pressure engines consume 20 °/。 less heat than turbines using steam at 225 lbs. / sq. in. Also, the high-pressure engine is particularly suitable for operating with high back-pressure, the exhaust steam being utilised for heating purposes (§ 188).

173. Steam Turbines.—Steam turbines have no marked advantage over reciprocating engines in point of steam economy until quite large units are concerned. In units exceeding 1 000 kW the turbine effects great saving in capital cost and space occupied, and its higher steam efficiency (though little superior to that of the best reciprocating engines) represents a large saving per annum. The most efficient steam turbines have 26-28 °/。 thermal efficiency, which is higher than that of gas engines, and is only exceeded by that of Diesel-type engines. The latter have not the compactness and simplicity of the steam turbine, and cannot yet be built in such powerful units (§ 179).

* For further information on reciprocating steam engines the reader may be referred to a chapter on the subject, by one of the authors (Mr. Neale), in Whittaker's *Mechanical Engineer's Pocket Book* (3rd edition).

From the facts stated in § 174 it will be clear that no universally applicable data can be given concerning the *steam consumption of turbines*. Also it will be clear that nothing less than an accurate statement, supplemented by full particulars concerning working conditions, is sufficient in practical working. At the same time, it is useful to know that under average working conditions * the steam consumption of a 500 kW turbine may be taken as 16-19 lbs. per kWh; of a 1 000 kW machine, as 15-16 lbs. per kWh; of a 2 000-5 000 kW machine, as $13\frac{1}{4}$-14 lbs. per kWh; and of 10 000-30 000 kW machines, as 10-11 lbs. per kWh. At $\frac{1}{4}$-load the steam consumption per kWh is from 15-20 % greater. Exhaust steam turbines, utilising steam at or near atmospheric pressure, usually consume between 30 and 40 lbs. per kWh. Given the steam consumption / kWh of a turbine at two loads, say full-load and $\frac{3}{4}$-load, the consumption at any other load or at no-load can be predicted accurately enough for practical purposes, by applying the Willans' straight-line law; the known consumptions are plotted against the values of load to which they correspond, and a straight line is drawn through the two points thus obtained. The consumption at any other load can be read at once from the line drawn. This method is not applicable to mixed-pressure turbines, owing to the use of different proportions of 'live' and 'exhaust' steam at different loads. Mixed-pressure turbines, which normally operate on part 'live' and part 'exhaust' steam, have about the same consumption as high pressure or exhaust turbines respectively when operating on live or exhaust steam alone.

Turbo-alternators of 20 000-30 000 kW capacity have become almost commonplace during recent years, and units up to 160 000 kVA capacity have been discussed seriously.†

The guaranteed steam consumption of the 40 000 kW, 1 500 r.p.m. turbines in the Gennevilliers station is 9·6 lbs. / kWh on full load (9·5, 9·9, and 11 lbs. / kWh on $\frac{3}{4}$, $\frac{1}{2}$, and $\frac{1}{4}$-load respectively), using steam at 350 lbs. / sq. in., 708° F.

At the time of writing, the largest set in operation is the 60 000 kW triple cylinder turbine of the Interborough Rapid Transit Co. (U.S.A.). This machine consists of a high-pressure turbine receiving steam at 205 lbs. / sq. in., 150° F. superheat, and delivering steam at 15 lbs. / sq. in. (gauge) to two low-pressure

* The B.E.S.A. recommends (in Report No. 72) that the turbine output at which highest steam economy is obtained should be 80 % of the maximum continuous output of the generator, except in special cases.

† See *Times Trade Supplement*, March 18, 1922, p. 91.

turbines. Each of the three elements drives a 20 000 kW, 25-cycle alternator at 1 500 r.p.m., and the total output available is 70 000 kW for 2 hrs., or 90 000 kW for ½ hr. The low-pressure turbines work with 29 in.-vacuum (30 in.-barometer) and the steam consumption on rated load is 11 lbs. / kWh, corresponding to about 25 % thermal efficiency. For output below 25 000 kW it is more economical to use the high-pressure turbine with only one low-pressure turbine.

The use of generating units exceeding, say, 10 000 kVA rating is limited to very large cities, where the load permits of practically continuous operation at high steam efficiency. The actual amount of labour required to operate such turbines is small, but it must be highly skilled, for obvious reasons. A serious consideration is the enormous loss of generator capacity on the system in the event of break-down in such a unit (*see also* § 145).

174. Effect of Steam Conditions on Turbine Efficiency.—The maximum total temperature (including superheat) of steam for use in power plants is limited to 700°-750° F.; above this temperature the mechanical strength of steel is reduced dangerously, and cast iron cannot safely be used for fittings or casings exposed to this temperature. The use of copper for steam pipes (as at bends) is dangerous at much lower temperatures. A total temperature of, say, 700° F. may be reached by using low pressure and high superheat, or high pressure and low superheat; the advantages of higher pressure are increased available heat drop (§ 166), and the smaller size of pipes required for the denser steam. The steam consumption of a turbine decreases about 0·1 % per 1 lb. / sq. in. pressure increase above, say, 150 lbs. / sq. in. Steam pressures of 300-350 lbs. / sq. in. are now used in many stations, and 400-500 lbs. / sq. in. will probably be used in the immediate future (*see* note on p. 273).

The reduction in steam consumption of turbines due to 10° F. additional superheat is about 1 % up to 100° F. superheat, 0·83 % between 100° and 200° F., and 0·72 % between 200 and 300° F. superheat. The limiting steam temperature (700°-750° F.) dictated by the strength of materials is already used extensively.

Turbines are extremely sensitive to vacuum, as shown by Table 18 (based on data due to G. Gerald Stoney, *Inst. Mech. Engrs.*, November 20, 1914). Practically the same savings as shown in col. 2 are obtainable with dry saturated steam as with superheated steam. With 28-28½-in. vacuum, the percentage saving in consumption would be increased (above the value given in Table 18) by about 1 % at ½-load and about 2½ % at ¼-load,

TABLE 18.—*Effect of Vacuum on Turbine Efficiency.*

Vacuum Between.	% Gain at Full Load and Per Inch of Vacuum, in Heat Available During Adiabatic Expansion. Using Steam at 160 Lbs. (Gauge) and 150° F. Superheat.	Using Steam at Atmospheric Pressure.
	% Per Inch.	% Per Inch.
23″ and 24″	3	9
24″ ,, 25″	3	10
25″ ,, 26″	4	11
26″ ,, 27″	5	12
27″ ,, 28″	6	14
28″ ,, 28½″	8 *	17 *
28½″ ,, 28¾″	9 *	20 *
28¾″ ,, 29″	11 *	23 *
29″ ,, 29¼″	13 *	27 *

using throttle governing; but would remain about the same at all loads, using nozzle governing. It is not possible to realise the full savings indicated above, particularly at very high vacua,† owing to terminal losses in the blading; nevertheless, there are few cases in which it does not pay to maintain the highest vacuum of which the equipment used is capable. Exhaust passages should be proportioned and shaped to give minimum loss of vacuum, and there should be minimum difference in vacuum between steam and air-pump connections to the condenser. A vacuum of 28 ins. (barometer 30 ins.) may be taken as a satisfactory standard value for high-pressure turbo-sets, and of 27½ ins. for exhaust turbines operating on steam at or near atmospheric pressure. Increasing the vacuum from 28 to 29 ins. practically doubles the volume per lb. of steam, and introduces evacuation and condensing problems of a mechanical nature which more or less completely offset the advantage derived from the greater available heat drop.‡

175. Steam Condensers and Auxiliaries.—The exhaust steam from engines or turbines may be condensed in various ways:—

* *Note.*—These are percentage gains *per inch* of vacuum; the actual gain between 28 and 28½ in. vacuum is 4 % (or 8½ %), and so on.

† Nearly the full theoretical gain is obtainable between 26-in. and 27-in. vacuum, but only 50-60 % of the theoretical between 28 ins. and 29 ins.

‡ A valuable paper is 'Choice of Steam Conditions in Modern Power Stations,' by L. C. Kemp, *Electrician*, June 30, 1922.

(1) In a *jet condenser*, it is mixed with jets of water. From 20-30 lbs. of water is required per lb. of steam condensed. If space be particularly valuable the water jet and exhaust steam may mix in a small chamber at the top of a pipe down which flows the mixture of condensing water and condensed steam; this form is called the *barometric condenser*, because the height of the downtake pipe must exceed the height of the water barometer (about 34 ft.), to which height water from the hot well is driven by atmospheric pressure when a vacuum is maintained in the condensing chamber.

(2) In an *atmospheric* or *evaporative condenser*, the exhaust steam passes through nests of tubes over which water trickles. Alternatively, the nest of tubes may be in the form of a hollow cylinder which is rotated about its axis, dipping meanwhile in a trough of water so that the outside of the tubes is covered by a film of water. Whereas the condensing water in jet and surface condensers is heated 50° F. or less, so that each pound of condensing water removes not more than 50 B.Th.U., the cooling water of an atmospheric condenser is *evaporated* and each pound removes about 1 000 B.Th.U. The atmospheric condenser requires only about 1-1½ lb. of water per lb. of steam condensed and is thus particularly valuable where water is scarce; the water used is, however, entirely lost. A natural or artificial current of air is required to carry away the water vapour, and in the saturated air (often 90 to 95 °/₀ humidity) of some tropical countries the type is almost useless, since very little evaporation is possible.

(3) In a *surface condenser* cold water is circulated through tubes over which passes the exhaust steam. From 50-70 lbs. of condensing water is required per lb. of steam condensed.

Atmospheric and surface condensers are more costly than jet condensers to build and maintain, but the condensate is not contaminated by the circulating water, the condensate is at higher temperature than that from a jet condenser, and all the condensate is used as boiler feed, hence there is minimum loss of heat from the steam circuit.

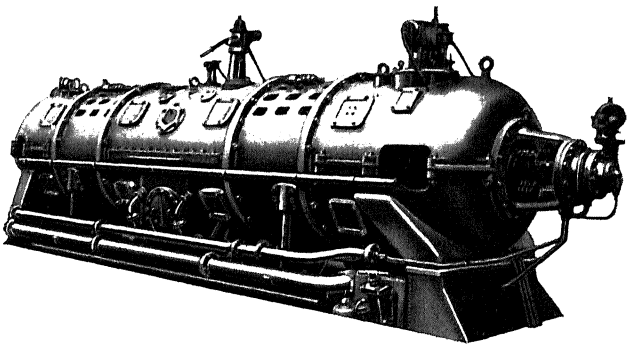
The large volume of circulating water required by a surface condenser cannot economically be treated to correct any corrosive properties which it may possess. This water is generally drawn from a river or canal through mechanical strainers, preferably of the self-cleansing type. The flow through the adits may be

reversed periodically to remove deposits of silt. The con
tubes should be made of an alloy which is not attacked
water used. Condensers in which the tubes are not longe
twice the diameter of the tube plates are more costly tha
densers of smaller diameter with longer tubes, but the
diameter design results in higher vacuum. Maximum vac
required at the turbine end of the exhaust passages, not
at the centre of the condenser.

If the supply of circulating water is limited, the water l
a surface condenser may be cooled for use again by allowin
flow down brushwood, laths, etc., in a cooling tower, up
air is blown by fans. Roughly 1 000 B.Th.U. per lb. of
consumed by the engine or turbine (or, say, half the ca
value of the coal burned below the boilers) has to be carried
by the air in the cooling tower. In climates where humi
high, the saturation of the air makes it difficult to cool th
densing water to a temperature making possible the mainte
of high vacuum.

Air from the feed water or leaking in to the steam cir
any point must be removed from the condenser by an air
The steam-jet ejector pump is simple and effective fo
purpose; the steam consumed equals about 1 % of the consum
of the engine or turbine, but practically the whole of the h
the steam jet passes to the 'hot well,' *i.e.* the tank in which
condensate is collected for use as boiler feed, so that the
is utilised in the warm water.

In order to allow for occasional air leaks in surface condenser s
provision should be made for the air pumps to deal with at least 1·3 lbs.
1 000 lbs. steam in moderate-sized plants, and for 1 lb. per 1 000 lbs. in large
It is well to arrange for 1 sq. ft. of condensing surface for every 5 lbs. pe
of steam to be condensed; such a condenser will run a considerable time w
cleaning and without much loss of vacuum, so that its cost is well invested.
modern air pumps, condensation of 7-10 lbs. per sq. ft. per hour is p
even with high vacua. As a standard for testing, a condenser with 1 sq.
7 lbs. of steam and a water velocity of 6 ft. per sec. in the tubes should
mit (3 days after tube brushing) not less than 450 B.Th.U. per sq. ft. of
per hr. per 1° F. difference in temperature between steam at inlet and
water temperature. A difference of 1° F. in the temperature of cooling water
about 0·3 % difference in turbine steam consumption (or, say, £200 capital
see § 174); hence it is a mistake to cut down the height of a cooling tower, on
the amount and efficacy of cooling chiefly depend (*see also* Selvey, *Journal*
Vol. 53, p. 114).

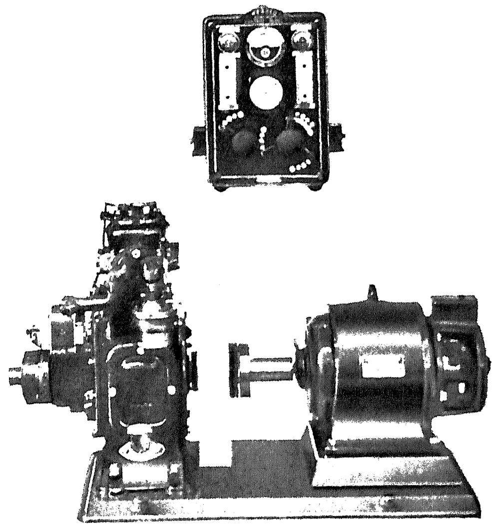


Brush Electrical Engineering Co., Ltd.

BRUSH-LJUNGSTROM TURBO ALTERNATOR; 3 000 KW AT 3 000 R.P.M.

There are no fixed guide blades in the Ljungstrom turbine. Two sets of blading are carried in concentric rings on the faces of two discs which run in opposite directions. Each disc is overhung on the shaft of an alternator, and the discs can be removed without disturbing the generators. The two alternators are in parallel and synchronise automatically whilst running up to speed. Steam enters at the centre and flows radially outwards to an exhaust chamber bolted directly to the condenser. The turbine is of the reaction type and, as the relative speed of the blades is twice the actual speed, very high efficiency is obtained. The number of rows of blades is one-fourth that of an ordinary reaction turbine. A 5 000 kW, 3 000 r.p.m. set using steam at 166 lbs. / sq. in., 662° F., with 28·9 ins. vacuum, consumes 10·36 lbs. steam / kWh at full load.

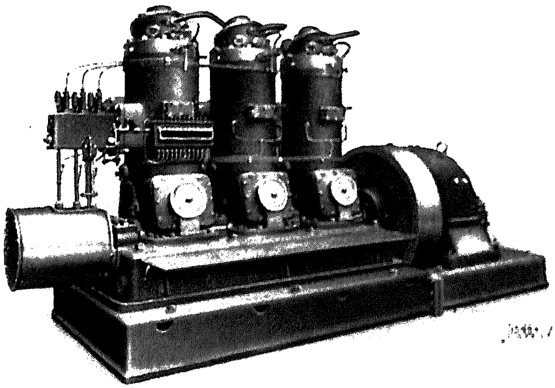
[*To face p.* 262.



Mark Webber, Ltd.

SEMI-AUTOMATIC HOUSE-LIGHTING SET.

This set combines all the control afforded by the usual accumulator charging board with electric starting and automatic stopping. A series field winding is used when the dynamo is run from the cells as a motor to start the engine; and a shunt field winding is used during normal service. Automatic stopping is effected by an ampere-hour meter with a bias on the 'charge' side, corresponding to the ampere-hour efficiency of the battery. The engine will run on petrol, benzol, alcohol, or town gas, and can be used as an independent unit. Standard sizes range from 1 to $2\frac{1}{2}$ kW and from 25 to 140 V.



Robey & Co., Ltd.

CRUDE-OIL ENGINE DIRECT-COUPLED TO A DYNAMO.

The engine illustrated operates on the two-stroke cycle (one working stroke per cylinder per revolution of the crankshaft). Any kind of crude or refined oil can be used, the engine can be started quickly and easily, and no water injection is required. Outputs up to 100 B.H.P. are obtainable from single- and twin-cylinder engines, and up to 300 B.H.P. from multi-cylinder engines of this type.

[*To face p. 263.*

The circulating and condensate pumps, and the air pump (if not of the steam-jet type) may be driven electrically or by steam. The cost of duplicate equipment is generally justifiable on the ground of reliability. If the auxiliaries are supplied solely from the main bus bars they may be incapacitated by an electrical break-down. Frequently a relatively small 'house turbine' is used to drive a generator providing current for station lighting and the driving of auxiliaries. The principal considerations are: (1) There should be minimum risk of the main generators being placed out of action by any failure in the auxiliary services. (2) As much as possible of the heat in the exhaust steam from all sources should be returned to the hot well. The energy consumption of condenser auxiliaries is generally from 3-5 % of the output of the prime mover.

176. Utilising 'Low-grade' Heat.—It is evident from the examples in § 166 that the exhaust from a steam engine or turbine contains a large part of the heat in the 'live' steam delivered to the prime mover. Roughly 60 % of the heat value of coal burned in an ordinary steam plant with condensing engines or turbines is delivered to the condensing water. Any reduction in the heat thus rejected constitutes an important saving. 'Low-grade' heat—*i.e.* principally the latent heat of steam which has been expanded in the prime mover—may be utilised by either or both of two methods, *viz.*: (1) By 'bleeding' steam from an intermediate stage in the expansion and using it to raise the temperature of the condensate, thus returning the heat of the bled steam to the feed water. (2) By using exhaust steam (or condensate) for industrial heating or for heating buildings, the back pressure on the engine or turbine being higher, the higher the temperature required in the heating service. The basic principle is the same in both cases; some of the heat in the live steam is used to produce mechanical power and the remaining heat (above atmospheric temperature) is used as heat. Greater saving is effected by method (2), when all the exhaust is used for heating, than by method (1) which is limited by the fact that the feed water cannot reasonably be heated above, say, 300° F. It is not commonly realised that even a 'super-station' cannot compete in overall efficiency with the smallest steam plant which can utilise its low-grade heat, unless the former can also dispose profitably of its low-grade heat. In most cases a small power plant

can find use for its exhaust steam more easily than a large central station (§ 188).

In collieries and other industrial establishments there are many excellent reciprocating engines which cannot economically be scrapped, but which do not utilise the expansion of steam as fully as could be done in turbines. In such cases exhaust steam from the engine can be utilised in low-pressure turbines which yield additional power (say 50 °/₀ of the engine output) without involving any additional consumption of fuel (*see also* Chapter 32).

177. Steam Accumulators.—Where exhaust steam is used to drive a low-pressure turbine or for heating or manufacturing processes, etc., some means may have to be provided for storing a temporary surplus of steam to tide over an ensuing temporary deficiency. This provision consists of a steam accumulator, which may be a tank of water (say an old Lancashire boiler suitably lagged) into which the exhaust steam is passed, the water then evaporating when the pressure on it is reduced by the demand for steam exceeding the inflow. Alternatively, the accumulator may consist of a counterbalanced, well-lagged 'gasometer' bell, in which the exhaust steam is stored, and from which it is taken as required. The advantage of the latter arrangement is that it imposes a lower back pressure on (and hence involves less loss of power in) the reciprocating engines supplying the exhaust steam —say ½ lb. per sq. in. as against 2½ or 3½ lbs. per sq. in. in the case of the water-storage system. The back pressure in a water-storage steam accumulator is sufficient to permit admission of live steam to a mixed-pressure turbine to be controlled by the pressure of the exhaust steam available at the moment. In the gasometer-type of accumulator, the variation in exhaust steam pressure is too small for this system of control to be effective, hence admission of live steam is then controlled, through oil-relays or otherwise, by the rise and fall of the storage bell.

Steam accumulators of the water-storage type can be used to store high-pressure steam if desired, and large reservoirs of this type are used in some installations to equalise the demand on the boilers. For example, relatively small boilers may operate continuously at full-load to feed a storage tank from which steam can be drawn intermittently at a rate far exceeding the steaming capacity of the boilers. For given variation in pressure, more

steam can be stored per cu. ft. of water at low than at high pressure.*

178. Fuels for Internal Combustion Engines.—The only fuels at present used commercially for internal combustion engines are gases or liquids which are converted, as far as possible, into gases prior to ignition. With reservations into which it is unnecessary here to enter, paraffin, petrol, alcohol, petroleum, town gas, and producer gas can all be used equally satisfactorily in relatively small engines up to, say, 100 B.H.P., the choice being determined mainly by the relative cost and ease of obtaining the several fuels. For engines of higher power petrol and town gas are generally too expensive, and the choice usually lies between some form of producer gas, coke-oven or blast-furnace gas, and petroleum (crude or refined) or tar oil.

The calorific value of *petrol*, *paraffin*, *and petroleum* is about 19 000-20 000 B.Th.U. / lb. The sp. gr. varies with the composition (each of these fuels being a mixture of 'fractions' distilling at different temperatures); typical values are: petrol, 0·68-0·72; paraffin, 0·75-0·85; crude petroleum, 0·85-0·95.

Tar oil, a by-product of the coking of coal, has a calorific value about 16 000 B.Th.U / lb. When this oil is used in engines it may be necessary to use an auxiliary injection of paraffin or other light oil to ensure ignition; the amount of light oil required is, *at all loads*, about 5 °/₀ of the full-load consumption of tar oil.

The calorific value of *alcohol* is usually between 11 000 and 12 000 B.Th.U. / lb. (according to the percentage of water contained) and the sp. gr. is about 0·82.

Natural gas contains up to 93 °/₀ of methane and has a calorific value of 800-1,100 B.Th.U. / cu. ft. The supply of natural gas is restricted to certain localities (mostly near oil fields) and is variable in quality and dwindling in amount. *Town gas* or *coal gas* is made by the distillation of coal in closed retorts; it may contain 40-45 °/₀ each of hydrogen and methane, and has then a calorific value of 600-700 B.Th.U. / cu. ft.; lately the calorific value has been reduced to 500 B.Th.U. or lower by the admixture of a considerable amount of water gas. Town gas is now sold, in Great Britain, on the basis of calorific value, the unit being the *therm* which equals 100 000 B.Th.U. The term *producer gas* includes a number of mixtures of carbon monoxide, hydrogen, methane, etc., with more or less carbon dioxide and nitrogen as diluents; these mixtures are the products of incomplete combustion of coal, coke, sawdust, peat, etc., in the presence of more or less steam. Simple producer gas or *air gas*, made by blowing or drawing air through a bed of incandescent carbon, consists mainly of carbon monoxide and has a calorific value from 70-100 B.Th.U. / cu. ft. *Water gas*, made by blowing steam and air alternately through incandescent carbon, may contain 50 °/₀ hydrogen and 35 °/₀ carbon monoxide, the calorific value being about 300 B.Th.U. / cu. ft.; if 'carburetted' by the addition of hydrocarbons,

* About 0·3 lb. of steam is stored per cu. ft. of water when the pressure rises from 265 to 280 lbs. / sq. in. (gauge), compared with 1·3 lb. of steam per cu. ft. of water when the pressure rises from 15 to 30 lbs. / sq. in.

water gas may yield about 650 B.Th.U. / cu. ft. Suction gas plant generally produces a mixture intermediate between air gas and water gas (§ 181). *Mond gas* is a producer gas made on a large scale and from bituminous coal with provision for utilising waste heat and recovering by-products (§ 169); its calorific value is about 150 B.Th.U. / cu. ft. *Blast furnace gas* contains 25-30 % of carbon monoxide and has a calorific value of about 90-100 B.Th.U. / cu. ft. The calorific value of coke oven gas is about 400-450 B.Th.U. / cu. ft.

Internal combustion engines are now available which can easily be adapted to operate on whichever liquid or gaseous fuel is cheapest at the time and place concerned.

179. Horse-power of Internal Combustion Engines.—The general formula for the horse-power of any reciprocating engine is:—

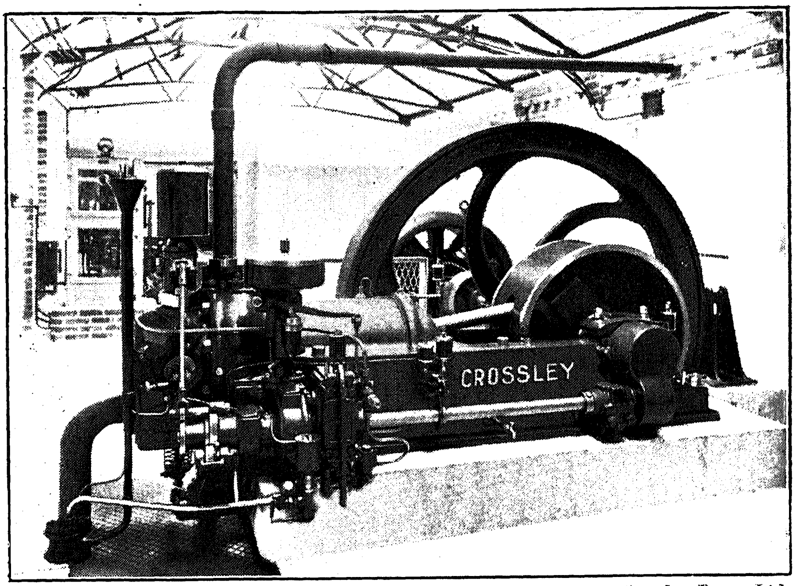
$$\text{Horse-power} = PLAN / 33\,000$$

where P = mean effective pressure on the piston during the working stroke, in lb. / sq. in.; L = length of stroke, in ft.; A = effective area of piston, in sq. in.; N = number of working strokes per min. The H.P. of a steam engine can be increased considerably above the rated H.P. by delaying the cut-off, thus admitting more steam to the cylinder and raising the mean effective pressure. In internal combustion engines, however, it is impossible greatly to increase the weight of fuel burned, beyond the value corresponding to the normal output for which the engine is designed. Though the overload capacity of internal combustion engines is small compared with that of steam engines, this does not limit the utility of the former for driving electric generators, provided that the engine be of suitable size; unfortunately some internal combustion engines cannot maintain an output equal to the rating which they are given in makers' catalogues.

An empirical but useful method of determining the size of internal combustion engine required to drive electric generators was published by W. A. Tookey in a paper read before the Association of Supervising Electricians, May, 1916. The data extracted therefrom in Table 19 relate to the normal full-load output which can be maintained continuously for 8 hrs.

For continuous (24-hr.) operation at full load the piston displacement per H.P. or per kW should be about 10 % greater than the values given in Table 19; on the other hand, for short periods the power developed may be 5-10 % higher than the value calculated from this table.

Example.—What is the normal full-load output of a town-gas engine with four cylinders, each 8 ins. dia. × 7 ins. stroke, running at 600 r.p.m.? The piston displacement is $(\pi(8)^2/4) \times 7 = 352$ cu. in. per stroke. On the four-stroke cycle there are 300 working strokes per min. in each cylinder, hence the total

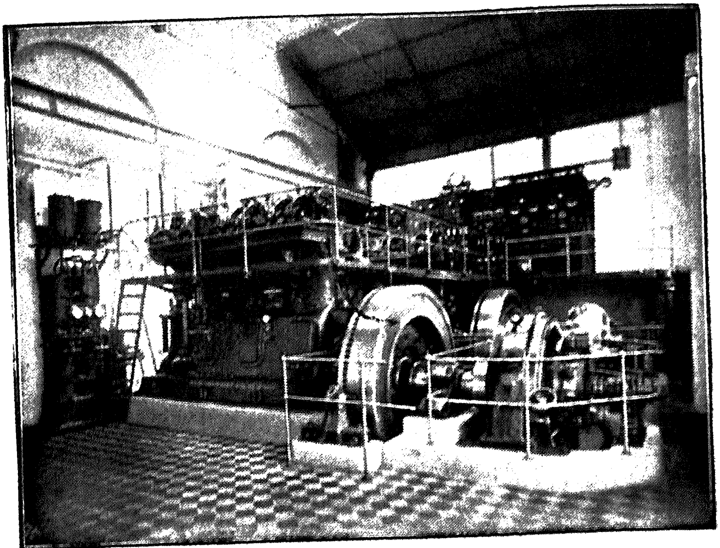


Crossley Bros., Ltd.

COLD-STARTING OIL ENGINE FOR REFINED, CRUDE, RESIDUAL AND TAR OILS.

The engine starts from the cold state without preheating, runs with moderate compression, and requires no air blast for the injection of fuel. It operates on the four-stroke cycle, and the oil pump injects a charge of oil into the combustion chamber in the form of fine spray. The fuel consumption at normal rated load ranges from 0·4 to 0·5 lb. / B.H.P.-hr., according to the quality of the fuel and the size of the engine. At half-load the total fuel consumption per hr. is less than 60 % of the full-load figure. The engine illustrated is rated at 43 B.H.P. normal (47 B.H.P. maximum), 250 r.p.m., and is direct coupled to a D.C. generator. The weight of the engine, including specially heavy fly-wheel for lighting service, is about 113 cwt. Similar engines are built from 19 to 130 B.H.P. (normal) single-cylinder, and from 38 to 260 B.H.P. double-cylinder.

[*To face p.* 266.



Mirrlees, Bickerton & Day, Ltd.

Diesel Oil Engines Driving D.C. Generators.

The illustration shows two 3-cylinder engines direct coupled to 160 kW dynamos. The cylinder diameter is 16 ins., stroke 19 ins., and normal speed 250 r.p.m. The guarantee figures for this size of engine are 0·44 lb. of fuel oil/B.H.P.-hr. at full load, and 0·46 lb./B.H.P.-hr. at ¾ load, assuming a calorific value of not less than 18,000 B.Th.U./lb. of fuel oil. Assuming the dynamo efficiency to be 91% at full load and 90% at ¾ load, the fuel consumption/kW.h. is 0·65 lb. at full load and 0·68 lb. at ¾ load. The actual consumption is generally lower under working conditions. The engine can be started (by compressed air) and placed on load in less than 2 mins. Standard sizes of this make of engine range from 50 B.H.P. single-cylinder to 750 B.H.P. six-cylinder.

[To face p. 267.

TABLE 19.—*Data for Calculating the Output of Internal Combustion Engines.*

	Town Gas.	Producter Gas From: Anthracite.	Producter Gas From: Coke.	Fuel Oil.	Paraffin.	Petrol.	Two-stroke Liquid Fuel Crank-case Compression.
(*a*) Mean effective pressure indicated, lb. / sq. in.	90	75	70	75	70	85	47
(*b*) Ditto, available at crankshaft, lb. / sq. in.	76	61	56	61	56	71	33
(*c*) Mechanical efficiency of engine (= *b* / *a*), %	84·5	81·3	80·0	81·3	80·0	83·5	70·0
(*d*) Piston displacement (impulse strokes only)—							
Cu. ft. / min. / B.H.P.	3·0	3·75	4·1	3·75	4·1	3·22	7·0
Cu. ft. / min. / kW *	4·5	5·6	6·1	5·6	6·1	4·84	10·5

piston displacement (impulse strokes) is 352 × 300 × 4 / 1 728 = 245 cu. ft. / min. From Table 19 the piston displacement required is 4·5 cu. ft. / min. / kW, hence the normal full-load output of the engine is: 245 / 4·5 = 54 kW approx.

It must not be overlooked that at high altitudes a larger engine is required; at 8 000 ft. the loss of power amounts to 20 or 25 % in oil and gas engines, or roughly 3 % per 1 000 ft. Furthermore, it is often found in hot climates that, even when allowance is made for altitude, oil engines will not continue to give their rated output, owing to the high temperatures experienced and the consequent decrease of mass of the volume of air in the cylinder; the loss amounts to about 1 % for every 6° F. above 60° F.

The data in Table 20 indicate the range of outputs for which various types of internal combustion engines are available, and the fuel consumption and thermal efficiency of each under favourable circumstances (*see also* §§ 180-183).

180. Oil Engines.—Under this heading may be grouped all engines which utilise liquid fuel, *viz.:* Petrol engines, alcohol engines, paraffin engines, Diesel engines, and semi-Diesel or hot-bulb engines. All these engines have high thermal efficiencies (Table 20, p. 268) and are thus at an advantage compared with steam plant for medium and small outputs (particularly below

* Assuming generator efficiency = 89 %.

TABLE 20.—*Horse-Power, Fuel Consumption, and Thermal Efficiency of Internal Combustion Engines (see also Table 15, § 167).*

Type of Engine.	Usual Range of Rated Output B.H.P.	Calorific Value of Fuel Used in B.Th.U. per Lb.	Fuel Consumption per B.H.P.-Hr. at Full Load.*	B.Th.U. per B.H.P.-Hr. at Full Load.*	Thermal Efficiency (B.H.P. Basis) at Full Load * %.
Oil Engines.					
Petrol	Up to 50 (aero 400)	20 000	0·55 lb.	11 050	23
Alcohol	Ditto	Various mixtures of alcohol and petrol 10 400-8 500			25-30
Paraffin	Up to 120	19 500	0·62 lb.	12 100	21
Diesel	12½-1 000 §	18 500	0·4 lb.	7 500	34
Semi-Diesel	5-600	18 500	0·42 lb.	7 700	33
Still (combined steam and oil)	—	18 000	0·375 lb.	6 750	37·7
Oil turbine	500-3 000 ¶	18 500	0·53 lb.	9 800	26
Gas Engines.					
Town or producer gas . .	Up to 250 **	Vari-able; see § 178	According to calorific value.	10 400	25
Blast furnace, coke oven, etc., gas	Up to 6 000 ‡				
Gas turbine	7 500-14 000 †				

* The figures in these columns apply to full-load operation of the largest engines in each class. As a rough guide it may be taken that the fuel consumption per B.H.P.-hr. is 10 % higher at 1¼ or ¾ times rated full load, 20 % higher at ½-load than at full load, and 50 % (or more) higher at ¼-load than at full load. In the smallest engines of each type it may be assumed, for the purpose of rough estimates, that the fuel consumption per B.H.P.-hr. is at least 50 % greater than in the largest engines of the same type.

† Claimed to be practicable; *see Times Trade Supp.*, Jan., 1922, p. 9; March, 1922, p. 91.

‡ Up to 300 H.P. per cylinder is developed in single-acting, four-stroke engines and up to 1 500 or 2 000 H.P. per cylinder in double-acting, four-stroke or opposed-piston, two-stroke engines.

§ Standard four-stroke Diesel engines are built up to 3 200 H.P. (8 cylinders), but engines exceeding 700 H.P. are rarely used on land. Two-stroke Diesel engines are built up to 4 000 H.P. (from 6 cylinders 29·13 ins. dia. × 40·15 ins. stroke), and as much as 2 000 H.P. has been obtained (experimentally) in a single cylinder engine of this type. Experiments have been made in Germany with a two-stroke Diesel engine developing 12 000-15 000 H.P. in six double-acting cylinders.

¶ These machines are still in the experimental stage, but it is claimed that they can be built for outputs up to 12 000 H.P.

** 1 500 H.P. from pressure producers.

500 H.P.). The elimination of the steam boiler and its appurtenances is often an important consideration, but the steam engine itself is simpler than any internal combustion engine and is more easily kept in good running order; this is especially important where skilled attendance is not easily available. Petrol-electric sets* are convenient and economical for such purposes as country-house lighting: they require no skilled attention for long periods, but it would be unwise to install them where skilled labour cannot be summoned when required.

The only advantage offered by alcohol compared with petrol engines is a possible saving in fuel costs. Paraffin, petroleum (crude or refined), and tar oil are undoubtedly cheaper fuels than petrol, and engines using these can be employed profitably in units up to, say, 100 H.P. for paraffin engines and 500–1 000 H.P. for engines using crude oil. Recent developments in crude oil engines make it probable that these will henceforward be used in the majority of installations requiring anything from a few horse-power up to 1 000 H.P. or so; for higher powers the steam turbine is generally the cheapest prime mover for land service. Though all oil engines show to best advantage on steady load near full-load rating, the relative increase in fuel consumption at partial loads is no greater than in steam plants. In small installations where the load, if any, can be supplied from batteries during part of the 24 hours, internal combustion engines eliminate the waste and trouble involved by 'banking' steam boilers.

Oil engines of the Diesel type are now used extensively in medium-sized power stations. Apart from high initial cost, the chief disadvantage of Diesel engines is that they require highly skilled attention; their use is therefore inadvisable in small stations. In this type of prime mover the liquid fuel, which may be crude oil, is sprayed gradually into the cylinder on the forward stroke and ignited by the high temperature caused by the extremely high compression of the air charge during the previous back stroke; there is therefore no actual explosion as is the case in ordinary oil or petrol engines, and no carburettor, vaporiser, or igniter is required. A modified type known as the 'semi-Diesel,' 'hot-bulb,' or 'surface ignition' engine is now much used. This

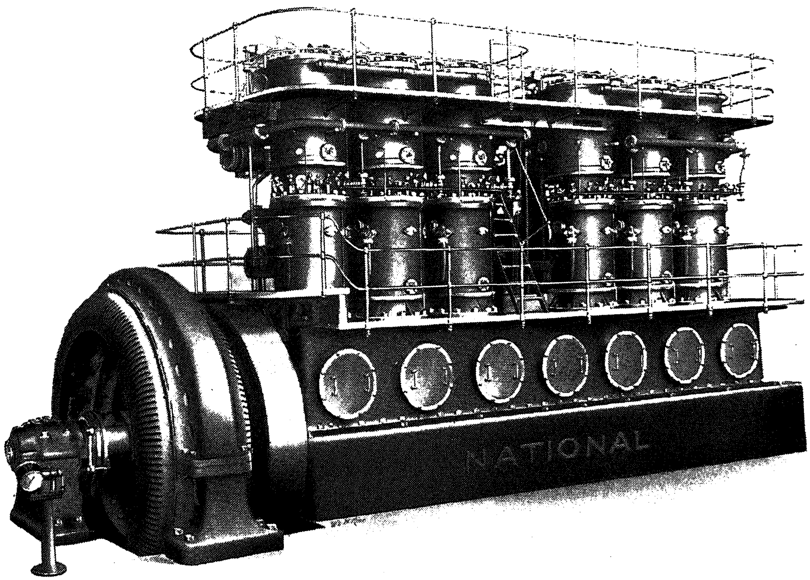
* Often of the self-starting type in which a small storage battery drives the dynamo temporarily as a motor and thus starts the engine if more than one or two lamps be switched on.

engine can work on crude oil, tar oil or any other fuel which can be used in Diesel engines, and its thermal efficiency is nearly as high as that of the latter. The distinctive feature of the semi-Diesel engine is that the compression pressure is lower than in the Diesel engine (say 350 lbs. / sq. in. compared with nearly 500 lbs. / sq. in.), hence the temperature reached by compression alone is not sufficient to ignite the fuel. A blow lamp or electric ignition device is used when starting the engine, and the combustion of the working fuel then keeps a special chamber or surface sufficiently hot to ignite the compressed charge (for fuel consumption data *see* §§ 167, 179).

181. Gas Engines.—Coal gas as distributed for lighting purposes is generally too costly for use in large power plants. Producer gas is made by passing air and more or less steam through incandescent fuel; where anthracite is available it is generally used, but coke, sawdust, and other refuse are also employed (§ 178). The oxygen of the air combines with the carbon of the fuel to form carbon monoxide, and the steam together with carbon also forms carbon monoxide and free hydrogen. In addition, certain amounts of marsh gas and carbon dioxide are formed. Some of the heat in the hot gases is used to raise steam, but the remainder is lost in the scrubbing tower; the thermal efficiency of the producer is from 70-85 °/$_\circ$ (Table 15, § 167). The gases as formed contain various impurities, which would foul the cylinder and valves, so they are cooled and purified in a scrubber, consisting of layers of coke with a water spray, and are then dried by passing through sawdust. The gas scrubber requires from $1\frac{3}{4}$-$2\frac{1}{2}$ gals. of water per B.H.P.-hr., and the gas generator about 0·6-1 pint per B.H.P.-hr. In the generator it is necessary that there should be a large mass of incandescent fuel for the saturated air to pass through; if the demand falls below about half normal the fire dies away.

Producer-gas plants have hardly realised the hopes held out for them; they show to best advantage in steady working and in sizes up to 250 or 400 H.P. The larger sizes generally show heavy repair and attendance costs, though much depends on the skill with which they are operated.

The high thermal efficiency of large gas engines makes them tempting where coke-oven or blast furnace gas is available, but it is found that a load factor of 35 °/$_\circ$ or over is required before they

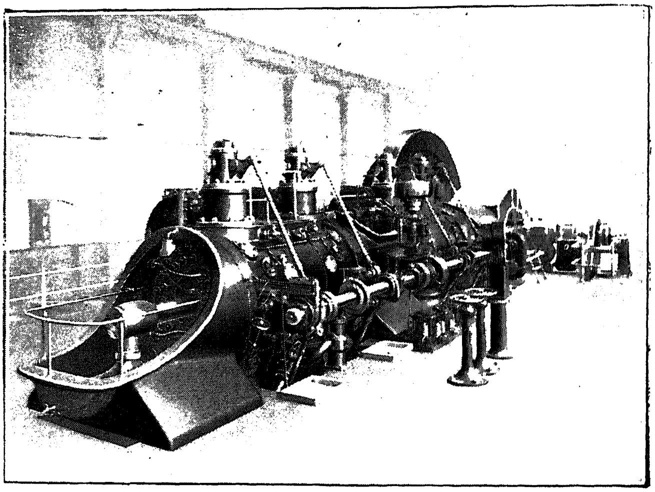


National Gas Engine Co., Ltd.

1 500 B.H.P. Vertical Tandem Gas Engine Driving an Alternator.

There are two cylinders in tandem over each crank and these fire alternately, so that there is a working stroke in one cylinder on every downward stroke. The space between the top piston and the intermediate cover is used as a buffer cylinder, so that the moving parts are cushioned on both the up and the down stroke. Forced lubrication is used, and no moving parts are water cooled. The engine is started by compressed air and can be run on all kinds of gases. The uniform turning moment and close governing obtained are important considerations where the driving of electric generators is concerned.

[*To face p.* 270.



Galloways, Ltd.

TANDEM, DOUBLE-ACTING, HORIZONTAL GAS ENGINE DRIVING AN ALTERNATOR.

The engine operates on the four-stroke cycle and has cylinders of 950 mm. diameter and 1 100 mm. stroke. Its output is 1 170 B.H.P. at 105 revs. per min. Engines of this type are designed to run on blast-furnace gas, coke-oven gas, a mixture of these gases, or on producer gas. Usual sizes range from 600 to 3 000 B.H.P. for single-crank engines (double these powers for two-crank engines). The engines are equally suitable for driving D.C. or A.C. generators, and it is claimed that the heat consumption does not exceed 10 000 B.Th.U. per B.H.P.-hr. at full load.

[*To face p.* 271.

can compete with steam turbine plant in central station practice, after allowing for capital and working costs. (For fuel consumption data *see* §§ 167, 179.)

182. **Humphrey Pump and Turbine Plants.**—The Humphrey pump may sometimes be used as the ultimate prime mover for generating electricity; for it bids fair to be the most economical water lift, and the overall efficiency of a turbine and generator under a perfectly constant head is also high. It is sufficient here to say that the pump uses the principle of resonance to keep a large amount of water pulsating backwards and forwards in a large pipe, by means of automatically-timed explosions, a certain proportion of the water being discharged at a higher level at each swing of the pendulum. From the high-level reservoir the water would return to the low level through a reaction turbine driving a generator. The loss of water would be confined to that caused by leakage and evaporation. The pump would be working under the ideal conditions of constant suction and delivery, and already fuel consumption as low as 0·93 lb. of anthracite per pump H.P.-hr. has been obtained under ordinary working conditions. A consumption not exceeding 1·6 lb. of coal per pump H.P.-hr. has been guaranteed, and 1·2 lb. is considered probable.

As a practical example, assume the consumption of coal to be 1·6 lb. per pump H.P.-hr.; further assume the cost to be 13s. 4d. per ton or 0·71d. per lb., which is equal to 1·14d. per pump H.P. hr. Assume the head to be 30 ft. then 1 pump H.P. hr. will be equivalent to 18⅓ lbs. of water per sec. or 0·29 cusec (§ 201) raised. With an overall efficiency of turbine and generator of 73 °/₀, the electrical output on allowing the same quantity to fall through the same head in 1 hr. will be 0·73 E.H.P.-hr. or 0·54 kWh. The consumption is therefore 2·9 lbs. per unit, costing 0·21d. These are figures which many central stations would envy.

The proposition would depend entirely on the existence of a natural storage site for water, as otherwise the capital cost of a large enough reservoir would be prohibitive. In this respect the problem somewhat resembles that which the advocates of tidal power (§ 230) put forward. A plant capable of giving an output of only 30 kW continuously would require 1 500 000 cu. ft. of storage (say 400 ft. × 400 ft. × 10 ft.) to give an hour's reserve supply on a 30-ft. head. Probably much less than an hour's supply would serve if the power were only to be used for distant irrigation pumping, which seems a promising field of development in the tropics.

183. **Gas and Oil Turbines.**—There is no reason to suppose

that internal combustion turbines will have the sam in point of higher thermal efficiency compared with gas and oil engines, that the steam turbine has comp ciprocating steam engines. Indeed the thermal effi and oil turbines will probably remain slightly lower large gas and oil engines, because the combustion is n the working space in the case of the turbines. Th offered by the turbine are the elimination of recipr and the possibility of developing higher power than ca be produced in reciprocating engines (Table 20, § 1 time of writing gas and oil turbines are still in the stage. The general principle employed, in the ma give most promise of success, is the combustion of ga air mixture in a series of chambers which are arra the products of combustion through nozzles to a tur The chief practical difficulty lies in the efficient utili energy developed by the fuel without overheating th chambers and turbine blades; in this connection th weakness of steel at high temperatures is an even factor than that of corrosion or burning. The hot the turbine may be used to raise steam for a turb which supplies air to the combustion chambers of the

184. Bibliography (*see* explanatory note, § 58).

B.E.S.A. Reports.

No. 42. Report on Reciprocating Steam Engines for Ele

No. 43. Specification for Charcoal Iron Lap-welded Boile

No. 53. Specification for Cold Drawn Weldless Steel Locomotive Boilers.

No. 120. Specification for Horizontal Gas Engines.

No. 125. Specification for Vertical Diesel Engines.

No. 132. Specification for Steam Turbines for Electrical

No. 135. Specification for Benzol for Motor Fuel.

No. 142. Specification for Vertical Semi-Diesel Engines

Books.

Natural Sources of Energy, by A. H. Gibson (University

Liquid Fuel and its Apparatus, by W. H. Booth (Consta

Low Grade and Waste Fuels for Power Generation, by J. (Constable).

Fuel and Lubricating Oils for Diesel Engines, by W. Sch

Steam Power Plant Engineering, by G. F. Gebhardt (Wil

Steam Boilers and Boiler Accessories, by W. Inchley (Ar

Boiler Inspection and Maintenance, by R. Clayton (Pitma

Heat Engines, by D. A. Low (Longmans).

Steam Turbine Theory and Practice, by W. J. Kearton (P

Steam Engine Valves and Valve Gears, by E. L. Ahrons (Pitman).
The Gas, Petrol, and Oil Engine, by Dugald Clark and G. A. Burls (Longmans).
High-power Gas Engines, by H. Dubbel (Constable).
The Diesel Engine, by A. Orton (Pitman).
Diesel Engines for Land and Marine Work, by A. P. Chalkley (Constable).
Lubricating and Allied Oils, by E. A. Evans (Chapman & Hall).

I.E.E. Papers.

Economical Production of Power from Coke Oven Gas, G. Dearle. Vol. 54, p. 646.
Gas Firing Boilers, T. M. Hunter. Vol. 56, p. 57.
High Pressure and High Temperature Steam in Large Power Stations, J. H. Shaw. Vol. 57, p. 73.
Effect of Air and Water on Materials used in Engineering Work, H. E. Yerbury. Vol. 57, Supp., p. 118.
Calculations Relating to High Pressure and High Temperature Steam with Interheating for Power Generation, W. M. Selvey. Vol. 58, p. 28.
Notes on Operating a By-product Producer Gas Plant, W. H. Patchell. Vol. 58, p. 417.
Developments in Large Steam Turbines, K. Baumann, Vol. 59, p. 565.
And many others too numerous to specify.

Miscellaneous.

Other sources of information include the Reports of the Fuel Research Board (Dept. of Scientific and Industrial Research); the Proceedings of the Institutions of Civil and Mechanical Engineers; and the technical press (*see also* Bibliography, §§ 199, 258).

Addendum to § 174 (p. 259).—Whilst these pages were in the press, information was published concerning a 1 000 kW experimental boiler, built by the Benson Engineering Co. and the English Electric Co. at Rugby, to work at 3 200 lbs. / sq. in. and 706° F., *i.e.* at the 'critical point' of steam. At this temperature, under this pressure, water occupies about three times its volume at 60° F. and is suddenly converted into steam without further increase in volume and without the absorption of any latent heat of vaporisation. The boiler consists of small-bore steel pipes with no drums. Distilled water is used as feed, and the steam is superheated to 785° F. After being throttled to 1 500 lbs. / sq. in., or possibly a higher pressure, the steam will be used in a special turbine exhausting at 200 lbs. / sq. in. It will then be reheated to 665° F. and the expansion completed in an ordinary turbine. The essential feature of the boiler is the generation of steam for use at 1 500 lbs. or over without the difficulties of spasmodic evolution. (D. Brownlie, *El. Times*, Vol. 63, p. 644.)

CHAPTER 7.

POWER PLANT DEVELOPMENT AND DATA.

185. Private Generation versus Purchase of Energy.— The relative advantages of private generation and purchase of energy, or, in other words, power generation in isolated plants and in central stations, are governed by many considerations. A central station effects savings in point of (i) the reduced capital costs per kW of large, compared with small, generating units; (ii) the reduced fuel costs and the lower attendance and maintenance costs per kWh made possible by the larger prime movers and higher load factor (§ 261); (iii) and the lower percentage of reserve plant required in a central power plant compared with small installations aggregating the same total capacity. These savings must, however, be compared with the capital and working expenses introduced by transmission and distribution equipment and the losses therein.* The purchase of electrical energy from a central station leaves an industrial consumer free to utilise all his available space and capital for the purpose of his own business, relieves him of the responsibility of operating generating plant, and generally secures greater reliability of supply. Other factors being equal, wholesale production of electrical energy in high-power stations operated by specialists in power production enables energy to be sold (at a profit) to the consumer more cheaply than he can produce it himself. The problem is, however, one which must be considered fully for each case on its merits. Though the capital cost per kW is higher for small than for large prime movers and generators (§ 195), the total cost per kW for the complete plant with buildings and site may be as low in an isolated plant as in a central station. By the judicious use of part-time labour, and particularly by the use of low-grade heat

* This aspect of the problem is discussed in 'The Economic Limits of Distribution from Coal-Fired Stations,' by W. B. Woodhouse, Inst. C.E. Engineering Conference, 1921.

(§§ 176, 188) for manufacturing purposes, the labour and fuel costs may be made to compare favourably with those of central stations. Again, the amount of power required by an industrial consumer may equal the total demand of a medium-sized community, in which case private generation amounts to installing a private central station in the immediate neighbourhood of the load; it is extremely difficult for purchased energy to compete with private generation in such cases, particularly if the latter has the advantage of cheap fuel (as at collieries, iron and steel works, etc., *see* Chapter 32) or very high load factor, as in railway workshops and the like.

The development of semi-Diesel engines (§ 180) makes it possible for any consumer, with a demand of, say, 150 kW or over and a reasonably good load factor, to compete closely with central station supply under average conditions and, whilst the general arguments in favour of centralisation are sound, there are so many factors involved that every industrial consumer should prepare estimates for himself.* The improvement of central station operation by the recovery of by-products from coal (*i.e.* the joint operation of gas works and electricity stations) and the utilisation of low-grade heat would make it impossible for any but exceptional private plants to compete with central stations. As matters stand, however, any private plant which embodies these principles can offset most, if not all, of the advantages of central stations in other respects (§§ 188, 191).

Many of the advantages of centralisation, and some other advantages as well, are derived from the electrical interconnection of existing generating stations (§ 186), and some of the latter may be stations originally erected as private installations for the supply of a particular works, colliery, etc.

186. Interconnection of Generating Stations.—Interconnection between two or more generating stations or transmission systems reduces the amount of reserve plant required in the system as a whole and improves the load factor and efficiency of operation. It is highly improbable that the load curves of the

* It is not easy to estimate accurately the cost of private generation owing to the difficulty of attaching a definite value to the factors of responsibility, reliability, etc. A good model for the preparation of estimates, taking into account all tangible factors, is to be found in 'Economy in Power Generation,' by R. G. Williams, *El. Ind. and Inv.*, Aug. 23, 1922.

two stations or systems will be identical, and even a few minutes' difference between the times of incidence of peak loads in the interconnected systems means that a considerable percentage of the generating plant in each system is available to help in supplying the peak load of the other. The difference between the thermal efficiencies of generating sets in large interconnected stations and those of the larger sets which could be used in a single central station supplying the same district is not great, and it is offset by the fact that the interconnected stations are at load centres and only a balance of power has to be transmitted through the 'tie lines' (§ 320) instead of the whole demand having to be transmitted from a central station. The effective capacity of two or more generating stations is often increased 25 °/₀ by interconnection, owing to the improvement of the diversity factor.

Interconnection between generating stations is now utilised on a most extensive scale, and generally the cost of inter-connection is very small compared with the value of the benefits derived. In America, interconnected transmission lines, fed from many generating stations, extend for hundreds of miles. Voltage differences form no obstacle to the interconnection of A.C. systems because the connection can be made through static transformers (Chapter 17); frequency difference is a more serious factor owing to the fact that it involves the use of frequency changers (*ibid.*) which are rotating machines; they suffer from 'swinging' or 'hunting' difficulties because a certain mechanical displacement of the rotor corresponds to a higher electrical displacement on the high frequency than on the low frequency side of the machine. The Thury constant current system has advantages where the interconnection of different stations is concerned (§ 317).

The greater the difference between the load curves of two stations, the greater the benefits to be derived from interconnection; this will be understood from Chapter 11. Interconnection is equally valuable where the time curves of available power differ, as in hydro-electric and wind power installations; indeed, many small water-power schemes, which would be commercially worthless if developed independently, can profitably be tied together and to an existing network (§ 187). Similarly, interconnection between two or more stations at different levels on one stream enables the electrical load to be distributed so that additional

water flow through the up-stream station can be used effectively, and without storage, at the down-stream station.

As explained in § 185, many private industrial power plants are able to operate at higher overall efficiency than central stations. By connecting them electrically the average thermal efficiency is improved, the hitherto independent consumer gains the advantage of increased security of supply, and the central station has additional generator capacity during some hours of the day and night. To take only one example, the industrial plant could supply some or all of the power required to carry its employees to and from work, this traction demand naturally preceding and following the internal demand of the works itself.

187. Automatic Generating Stations. — In the automatic petrol-electric generating set (§ 180), the engine starts automatically directly the demand exceeds the capabilities of the small storage battery employed at other times. The same or the converse principle is applied to the utilisation of small water-power developments, particularly on low falls with irregular flow. A suitable turbine is coupled to an induction generator (§ 144), and the latter is switched automatically in parallel with an existing transmission system whenever the load on the system demands additional generator capacity or whenever there is sufficient water-power available to justify operation of the set, as the case may be. Wind-power (§ 165) may be utilised in the same way. Attendance costs are practically eliminated by the automatic gear * and, in the case of low falls, the dams erected for automatic generating stations may be useful in flood prevention and irrigation.

188. Utilisation of Waste Heat. — Notwithstanding such advances as the use of regenerative furnaces in the iron and steel industries and of continuous kilns in ceramic manufactures, it is probable that 80 or 90 °/₀ of the heat value of all coal burnt is wasted. For the reasons explained in § 166, the heat engine cycle is inherently and inevitably wasteful. The fact that the absolute zero of temperature is far below atmospheric temperature places a low and definite limit upon the maximum efficiency of even a 'perfect engine.' Hitherto, effort has been concentrated mainly upon raising the efficiency of actual engines as near as possible to the theoretical value, and in this work a

* For discussions as to the possibilities of automatic generating stations and descriptions of successful installations see *Gen. El. Rev.*, Vol. 22, pp. 846, 960, 963.

great measure of success has been attained (§ 167). An increasing amount of attention is now being given, however, to the utilisation of 'low grade' heat in the exhaust steam or gases from engines, and in this field there are possibilities of far greater savings than could, by any means, be effected in the prime movers themselves.

For example, suppose that 1 000 000 kWh are generated in a certain time by ten 100 kW steam engine driven sets operating at 8 % thermal efficiency. The heat consumption of these sets would be $3\ 412 \times 10^6 / 0{\cdot}08 = 4{\cdot}26 \times 10^{10}$ B.Th.U. If the same quantity of energy were developed by a 20 000 kW turbo-set operating at 28 % thermal efficiency the heat consumption would be $3\ 412 \times 10^6 / 0{\cdot}28 = 1{\cdot}22 \times 10^{10}$ B.Th.U., the generator losses being neglected in both cases. Thus, by going from about the lowest to about the highest thermal efficiency in the steam prime mover there is effected a saving of $(4{\cdot}26 - 1{\cdot}22)\ 10^{10} = 3{\cdot}04 \times 10^{10}$ B.Th.U. If now the 100 kW steam engine sets be arranged so that the heat in the exhaust steam is utilised in hot water supply and for heating rooms, etc., the overall thermal efficiency of these sets may be raised to 60 % by the utilisation of (60 − 8) % of $4{\cdot}26 \times 10^{10}$ B.Th.U. ($= 2{\cdot}21 \times 10^{10}$ B.Th.U.) in the form of low-temperature heat. This saving amounts to $2{\cdot}21 / 3{\cdot}04 = 72{\cdot}5$ % of the saving which could be effected by the use of the 20 000 kW set. A corresponding saving could, of course, be effected in the 20 000 kW set by similar utilisation of low-temperature heat.

As thus considered, the example shows how small engines *with* utilisation of low-temperature heat may approach or surpass the efficiency of modern super-stations (*without* low-temperature heat recovery). The super-station still shows a considerable saving in heat consumption for given electrical output, but the small sets are also carrying a large heating load and giving high overall efficiency under conditions to which a large turbo-set might be inapplicable, *e.g.* it by no means follows that ten 100 kW installations could be served from a 20 000 kW set.

The distinction between the two cases is shown clearly by considering the output from equal coal consumption instead of the heat consumption for equal electrical output. From 100 tons of coal the small engines would yield the equivalent of 8 tons as electrical energy and of 52 tons as low-temperature heat, whereas the turbo-set would yield the equivalent of 28 tons as electrical energy (neglecting generator losses as before). The net waste would be 40 tons of coal in the first case and 72 tons in the second, but the turbo-set would yield $28 / 8 = 3\frac{1}{2}$ times as much electrical energy as the engine sets, and the advantage of the latter, under the conditions considered, would depend upon there being use for the equivalent of 52 tons of coal in the form of low-grade heat. It must again be emphasised that the relative inferiority of the turbine in the case considered is due to its being operated *without* utilisation of low-grade heat.

The general possibilities and difficulties of utilising waste heat will be seen from the preceding example. In every heat engine installation there is more than 50 % (generally more than 75 %) of the total heat consumption which can be utilised *if there is a sufficient demand for low-temperature heat.* Given this

demand it is generally a very profitable proposition to meet it by using rejected engine heat. In America, many central stations distribute hot water or low-pressure steam for 'district heating,' but in this country the milder climate, the more scattered communities, and the national preference for a glowing fire militate against the commercial prospects of such a scheme. Nevertheless, the cost of pipe lines is not prohibitive, the losses in distribution are low (in some American installations the consumers receive 83 °/ₒ of the steam leaving the station), and the possible saving in fuel is so great that experimental installations in densely populated areas are certain to be made and are likely to be successful. The supply of exhaust steam to adjoining establishments for industrial purposes is already practised in this country.* If high-pressure steam is required for such purposes it can be obtained by raising the back pressure of the engine or turbine (§ 176); in other words, the prime mover is used as an energy-yielding pressure-reducing device,† and the electrical energy is a by-product reduced in amount, compared with the output obtainable by full expansion, but obtained in conjunction with high overall thermal efficiency. Waste heat boilers are now commonly fitted to the exhaust of large gas engines (§ 181). The most difficult class of waste heat to utilise is the low-temperature heat in the circulating water of turbine condensers; so long as the present practice is followed of developing as much power as possible in the turbine, by continuing the expansion to the highest attainable vacuum, the rejected heat is bound to be at very low temperature (about 95° F., 35° C.), and the most promising application ‡ yet suggested for this heat is in warming greenhouses and in heating the soil of market gardens for forced crops.

189. Choice of Type and Power of Prime Movers.—This problem is one of many parts all of which are correlated to such an extent that a final solution in any particular case can only be obtained by comparing several alternative equipments. Having determined the probable maximum demand (M.D.) in kilowatts (Chapter

* Information concerning British and American installations for the utilisation of exhaust heat is to be found in papers and a joint discussion, *Jour. I.E.E.*, Vol. 60, pp. 265-86.

† Small turbo-generators up to 100 kW output are thus used instead of throttle valves in sugar refineries.

‡ The possibilities of this scheme are discussed by H. M. Sayers, *El. Rev.*, Vol. 90, p. 115.

11), the question of probable extensions must be considered. If the installation is a large one extensions may be met by installing additional generator sets, but in the case of a small plant the full capacity should be laid down at the start, the probable kilowatts M.D. of the extensions being added to that already determined. If a secondary battery, capable of keeping the installation at work for a whole day, is included in the scheme, a single generating set may be sufficient in small installations; but it is very seldom advisable to attempt running without spare plant. In out-of-the-way places, a serious break-down may mean a delay of weeks in effecting repairs or obtaining spare parts. Two identical generating sets, each capable of running the whole of a small installation, are generally advisable. If the plant is of moderate size, three identical sets are recommended: one to work at times of light load beyond the capacity of the battery, two to work together at times of heavy load, and the third as spare; in yet larger plants, at least two reserve sets are required so that there may always be one set ready for immediate service whilst the other is undergoing overhaul or repair. If a battery is not installed, and the plant is large enough to warrant it, a small petrol or oil-driven generator is useful for the light-load hours, as it will work at higher efficiency than a larger set only lightly loaded. Generally speaking, for very small installations, an oil engine set and battery is the best equipment, or alternatively a suction-gas plant with gas engine and battery. For larger installations the relative prices of oil and coal must determine whether a Diesel oil engine or a steam engine is the best prime mover. With the exception of large industrial establishments, isolated installations are seldom large enough to warrant the use of steam turbines, and the use of water power is necessarily restricted by natural conditions, apart from the high cost of its development.

Allowance must be made for the relative cost of the fuel employed when comparing prime movers of different thermal efficiencies (Table 15, § 167), for example, an engine using 25 % of the heat value of oil at £4 per ton will cost as much, for fuel, as a steam engine utilising $12\frac{1}{2}$ % of the heat from coal at £2 per ton. In addition, the capital and maintenance charges per kWh must be considered; saving in capital cost is important where the load factor is low, and in running costs where the load factor is

high (§§ 263, 264).* As a general guide it may be taken that suction gas or oil engines are cheapest for outputs up to 100 kW; for higher outputs up to 400 kW or so, the 'locomobile' steam boiler and engine can hardly be beaten for convenience and economy, though it has keen competitors in the Diesel and semi-Diesel engines. Similarly, for outputs from 500 to 1 500 kW the uniflow and Lentz engines are rivalled closely by Diesel and semi-Diesel engines; with cheap oil the Diesel and semi-Diesel engines would be at a considerable advantage.

Comparing steam engines and steam turbines, up to about 1 000 kW there is no advantage in using steam turbines, either in prime cost or efficiency. Table 21 gives the approximate steam consumption (lbs. per kWh) and cost F.O.B. in British port of modern combined sets (prime mover and generator) of both types in three sizes, including condensers and exciters, assuming superheated steam at 175 lbs. pressure and working with a vacuum of 27 ins. (*see also* Table 27, § 195).

TABLE 21.—*Cost of Combined Sets (Steam).*

Size.	400 kW.		500 kW.		1 000 kW.	
	Turbine.	Engine.	Turbine.	Engine.	Turbine.	Engine.
Total cost (pre-war) †	£3 120	£2 640	£3 300	£3 200	£4 800	£6 000
Cost per kW (pre-war)†	£7·80	£6·60	£6·60	£6·40	£4·80	£6·00
Steam consumption (lbs. per kWh)—						
Full load . .	19·1	17·2	16·3	16·6	15·3	16·0
¾-load . . .	20·7	17·6	17·5	17·0	16·1	16·3
½-load . . .	22·9	19·0	19·1	18·5	17·9	17·7

For outputs exceeding 1 000 to 1 500 kW the steam turbine is generally the most economical prime mover, but large gas engines can be used to advantage where coke-oven or other cheap gas is available, especially if the annual load factor (§ 261) be high, say, 50 % or over.

The economic advantage of coking coal amenable to this process, and recovering the by-products of the distillation, has already been pointed out (§ 169). Surplus gas from coke ovens may be utilised in gas engines, or it may be burnt under

*An article on 'The Choice of Prime Movers,' by K. Baumann, *Brit. Westinghouse Gaz.*, 1914, 1915, dealt with the problem in detail, and gave many charts and tables which could easily be brought up to date.

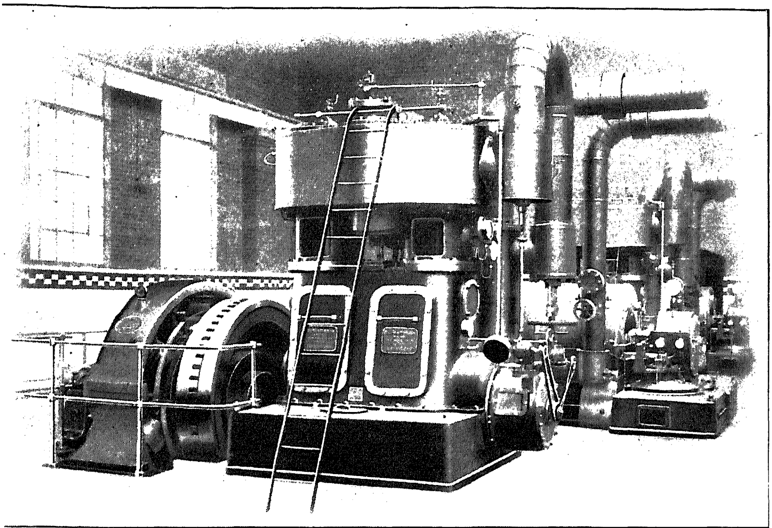
† Pre-war and post-war costs are compared in Table 27.

steam boilers (preferably of the Bonecourt type, § 170). The former course may appear more direct and efficient, but steam turbines can be built in much larger units than gas engines (§ 179); also, they occupy much less space and can be used with alternators of higher speed and therefore more economical construction. It is often overlooked that large modern steam boiler and turbine plant yields an overall thermal efficiency comparing favourably with that of gas engines on full load (Table 15, § 167), whilst on low-load factors advantage certainly rests with the steam plant. In the Powell Duffryn collieries (Sparks, *Jour. I.E.E.*, Vol. 53, pp. 389 *et seq.*), certain 1 500 kW coke-oven gas engine and alternator sets averaged 12·8 B.Th.U. per Wh on full load (corresponding to 26½ °/₀ thermal efficiency), as compared with 20·3 B.Th.U. per Wh (16·8 °/₀ thermal efficiency) in the case of a modern 5 000 kW turbo-alternator; in this particular case it was possible to so distribute the total load that the gas plant operated under 72 °/₀ annual load factor.

The fine reciprocating engines of 3 000-5 000 kW capacity set to work in the early years of this century were speedily rendered obsolete by the lower steam consumption of the steam turbine, and the latter is at present unchallenged as the prime mover in the largest fuel-burning stations, where units exceeding 5 000 kW are required. In such stations it is generally found that 15 000-20 000 kW is the most economical size of unit. In very large stations, larger units may be justified, the best size being then 30 000-35 000 kW, but the cost of keeping reserve units to eliminate the risk of wholesale interruption of supply (in the event of break-down in such large sets) then becomes a serious consideration.

The total generator capacity in any power house is usually between 50 and 70 °/₀ (or, say, two-thirds) of the total kW capacity of current-consuming devices connected to the station. Not less than 25 °/₀ of spare plant (reckoned on that required to supply the maximum demand) is the minimum for security of supply, and a 50 °/₀ margin is desirable if the demand is growing rapidly; as already stated there should be at least two large sets in reserve to allow for one set being dismantled.

190. Selection of Units for Service.—In any existing power house there is opportunity for effecting a saving by judicious selection of the plant put in service to supply any particular load. The total capacity of the working sets must exceed the actual load by a reasonable margin (depending on the probable load within the next ½ hr. or 1 hr., which can be predicted with sufficient accuracy from the known form of the daily load curve). There are generally available several combinations of sets which

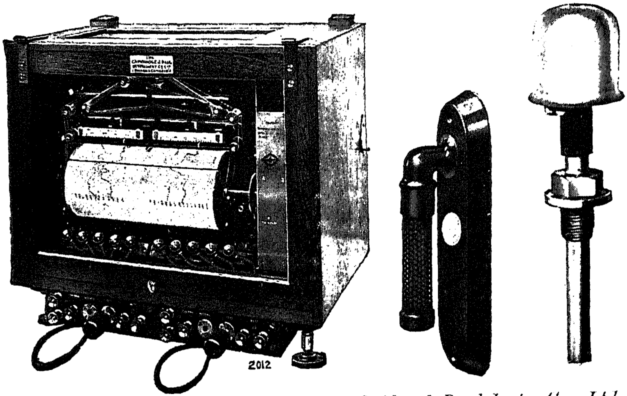


Belliss & Morcom, Ltd.

ꝛECIPROCATING STEAM ENGINES IN CONJUNCTION WITH MIXED PRESSURE TURBINES.

The installation shown comprises two 400 kW Belliss compound engines, each xhausting to a 350 kW mixed pressure turbine and condensing plant made by the ame firm. The overall efficiency of reciprocating engines exhausting, at atmos-heric pressure, to condensing turbines is high, and the combination is flexible in peration. Normally the engine and mixed pressure turbine are run in conjunction, ut the engine can be run independently—exhausting to atmosphere or straight to he condenser. The turbine can also be used independently, and it can utilise any ow-pressure steam which may be available, *e.g.* the exhaust from steam hammers. ʒy adding mixed pressure turbines to an existing installation of reciprocating ngines, the output and efficiency of the plant can be increased.

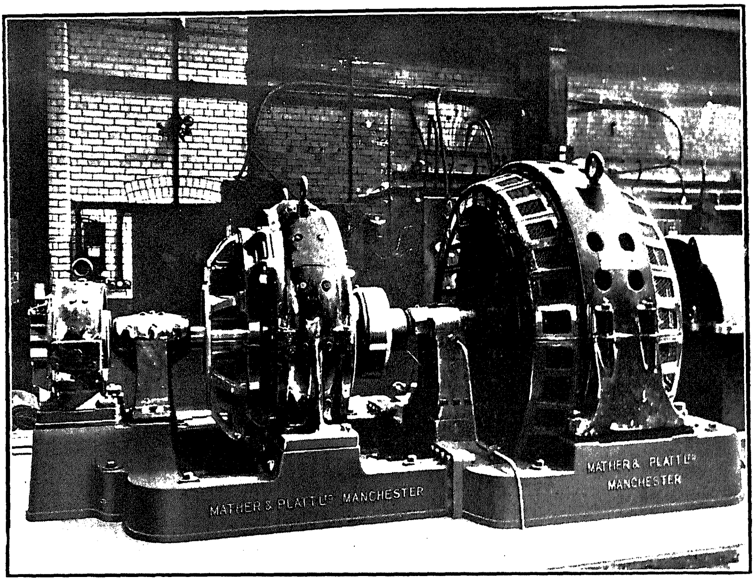
[*To face p.* 282.



Cambridge & Paul Instr. Co., Ltd.

ELECTRICAL RECORDER AND RESISTANCE THERMOMETERS.

This recorder makes four records simultaneously, *e.g.* CO_2 percentage, and feed water, flue gas, and steam temperatures. The pointers of two galvanometers register their positions at, say, 1 min. intervals by being depressed automatically on to inked threads of distinctive colours. The percentage of CO_2 is measured by a bridge circuit depending on the different rates of cooling of similar hot wires in air and in the flue gas respectively. The resistance thermometers are protected in various ways to suit service conditions; that in the centre is for measuring air temperatures indoors, and the other is for positions under pressure, such as steam or bearing temperatures.



Mather & Platt, Ltd.

DOUBLE CURRENT (A.C. AND D.C.) GENERATING SET.

It is necessary in many districts to supply A.C. to some consumers and D.C. to others. In such cases, the steam consumption can often be reduced by using a single turbine to drive both types of generator. The illustration shows a steam turbine driving a 750 kW, 833 kVA, 2 200 V, 100-cycle, single phase alternator, and a 500 kW, 550 V, D.C. generator. The small machine at the end of the shaft is an 'overhung' exciter.

[*To face p.* 283.

would provide the desired total capacity and, where possible, that combination should be used which consumes least steam. The 'Willans' line' should be plotted for each generating set showing the steam consumption per hr. (including the consumption in auxiliaries) as a function of the output in kW. Thence a table or a chart can be prepared to show at once the most economical combination of sets for any particular load. On a falling part of the load curve the sets in service may be overloaded temporarily but, if a peak load is approaching, allowance must be made for this when deciding upon the sets to be placed in commission.

In large modern stations, and particularly in those interconnected with other systems (§ 186), a 'load despatcher' is given full information concerning the service characteristics of all machines and stations, and being in telephonic communication with all parts of the system, he is made responsible for the putting of plant in and out of service and for all main switching operations.

191. Power House Losses; Overall Efficiency.—The overall efficiency of electricity stations is commonly expressed in terms of the fuel consumed per kWh generated. Statistics prepared on this basis by the Electricity Commissioners are summarised in Table 22; the average coal consumption per kWh generated in steam stations was 3·11 lbs. in 1921-22 (396 stations).

As, however, the calorific value of the coal burnt varies widely (say from 10 000 to 13 000 B.Th.U. / lb.), such data are of limited value, and it is much better to state the efficiency in terms of the heat consumption per kWh generated. The heat equivalent of 1 kWh is 3 412 B.Th.U., hence a consumption of 3·11 lbs. of coal (of calorific value 10 500 B.Th.U. / lb.) per kWh corresponds to a heat consumption of $3{\cdot}11 \times 10\,500 = 32\,650$ B.Th.U. / kWh, and an overall thermal efficiency of $3\,412 \times 100 / 3{\cdot}11 \times 10\,500 = 10\frac{1}{2}$ % approx. About 20 000 B.Th.U./kWh is consumed in average large modern stations with steam turbo-alternators operating at, say, 50 % load factor, and 17 000-17 500 B.Th.U. / kWh (*i.e.* 20-19·5 % thermal efficiency) is about the best result which can be obtained in such stations. Assuming that 20 % of the heat value of the coal is delivered to the bus bars as electrical energy, the distribution of the 80 % lost is roughly as follows (in percentage of heat input at the grate*): Boiler losses 20 %; rejected in

* These percentages must not be confused with the percentages of loss in terms of the input to the individual parts of the system; for instance, the

TABLE 22.—*Fuel Consumption of Generating Stations in Great Britain.*

Number of kWh Generated at Station per annum.	Steam Stations.				Gas Producer Stations.				Oil Engine Stations.			
	No. of Stations.	Fuel Consumption / kWh Generated. Average.	Fuel Consumption / kWh Generated. Lowest.	Highest Thermal Efficiency. (Approx.)	No. of Stations.	Fuel Consumption / kWh Generated. Average.	Fuel Consumption / kWh Generated. Lowest.	Highest Thermal Efficiency (Approx.).	No. of Stations.	Fuel Consumption / kWh Generated. Average.	Fuel Consumption / kWh Generated. Lowest.	Highest Thermal Efficiency (Approx.).
Million kWh		lbs.	lbs.	%		lbs.	lbs.	%		lbs.	lbs.	%
Over 200 . .	2	2·10	1·74	17·20	—	—	—	—	—	—	—	—
Between 100 and 200	7	2·41	1·98	15·25	—	—	—	—	—	—	—	—
,, 50 ,, 100	10	2·30	1·70	16·50	—	—	—	—	—	—	—	—
,, 25 ,, 50	25	3·00	2·22	14·10	—	—	—	—	—	—	—	—
,, 10 ,, 25	65	3·38	2·04	15·20	—	—	—	—	—	—	—	—
,, 5 ,, 10	51	3·98	2·80	11·17	—	—	—	—	—	—	—	—
,, 2·5 ,, 5	48	5·03	3·24	11·21	—	—	—	—	2	3·16	2·79	8·56
,, 1·0 ,, 2·5	74	5·69	3·56	9·12	2	1·74	1·67	15·12	6	1·90	0·65	28·10
,, 0·5 ,, 1·0	39	7·68	4·61	7·20	4	3·35	2·33	11·25	11	1·86	0·65	29·15
,, 0·25 ,, 0·5	26	8·58	5·44	5·30	14	2·82	1·83	12·44	18	1·65	0·67	27·45
,, 0·10 ,, 0·25	22	12·80	5·89	6·85	19	2·77	1·39	15·60	9	1·82	0·69	27·50
,, 0·05 ,, 0·10	18	20·90	6·80	4·10	15	2·32	1·97	12·30	1	—	—	—
Under 0·05 . .	9	10·33	4·44	6·07	6	4·06	3·30	7·95	5	1·83	1·54	12·29
TOTALS . . .	396	3·11	—	—	60	2·64	—	—	52	2·08	—	—

NOTE.—Where the calorific value of the fuel was not specified on the returns, the following average values (B.Th.U. / lb. throughout) were used for calculating the thermal efficiency: Coal (for steam stations), 10 500; anthracite (for gas producer stations), 13 000; coke (for steam and gas producer stations), 6 000; oil (for steam and oil engine stations), 18 000.

condenser 52 %; mechanical losses in turbine 5 %; alternator and transformer losses 1 %; losses in auxiliary services 2 % (*see also* Table 24, § 193).

According to W. M. Selvey (*El. Rev.*, Vol. 91, p. 727) the maximum efficiencies which can be expected in new plants are as in Table 23; these are higher than the efficiencies at present realised and represent possibilities in the future for plants designed to take full advantage of present-day experience.

TABLE 23.—*Probable Limits of Efficiency in Steam-Driven Generating Stations.*

	New Stations with Generating Sets of (Each).		Largest Stations with High Pressure Steam and Inter-heating.
	3 000 kW.	6 000 kW.	
(*a*) Boiler efficiency	0·78	0·81	0·85
(*b*) Thermo-dynamic efficiency of turbine cycle	0·34	0·36	0·40
(*c*) Mechanical efficiency of turbo-generator .	0·70	0·73	0·85
(*d*) Ratio of kWh at bus bars to kWh generated *	0·75	0·80	0·85
Overall efficiency (= $a \times b \times c \times d$) . . .	0·139	0·170	0·245
B.Th.U. / kWh at bus bars	24 550	20 050	13 930

From Chapters 6 and 11 it will be clear that load factor is of the utmost importance in determining the overall efficiency of power plants (*see also* § 217). In general, gas and oil engine plants are affected more adversely than steam plants by low load factor because the efficiency of internal combustion engines falls off more rapidly at fractional loads, but this can be compensated to some extent by the installation of a suitable range of sizes; advantage is then derived from the fact that internal combustion engines have no stand-by losses.

When comparing the consumption of (say) 17 500 B.Th.U. / kWh in a large modern station with the 22 500 B.Th.U. / kWh attainable in a small isolated plant it must be remembered that the distribution of energy from the large station involves at least

mechanical loss in the turbine = 5 % of the coal value, but 5 × 100 / (100 − 20 − 52) = 17·9 % of the input to the turbine after deducting the boiler and condenser losses (*see also* § 193).

* Allowing for consumption in station auxiliaries and for operation and machine load factor losses.

two pressure transformations (possibly four) and also the losses in the transmission line. Allowing for three transformations (each at 98 % efficiency) and for 10 % loss in transmission, the overall efficiency from station to consumer is 0·98 × 0·98 × 0·9 = 0·865, and the 17 500 B.Th.U. / kWh generated becomes 17 500 / 0·865 = 20 200 B.Th.U. / kWh delivered. Allowing also for the easier utilisation of heat from private power plant (§ 188) it will be seen that the supposed advantages of centralisation may be reduced or even non-existent (§ 185). In many instances a good case could be made for decentralisation.

192. Control of Power House Efficiency.—The complete determination of power house efficiency involves the installation of measuring instruments on every piece of the equipment, the taking of readings at frequent, regular intervals, and the calculation of results therefrom. The trouble and expense of obtaining these results is justifiable in large stations, provided that the information derived is applied to the improvement and maintenance of efficiency. In smaller stations a less elaborate procedure is required, but some definite record and comparison of fuel consumption, water consumption, and electrical output should always be maintained, in addition to suitably tabulated records of expenditure on oil, general stores, repairs, etc. Probably the simplest and best method of controlling the overall efficiency of a steam-driven station is as follows: * The weights of coal burnt and of water evaporated per shift are plotted (on separate sheets) against the kWh generated. After doing this for a fortnight or so it will be found that straight lines can be drawn showing what is an average consumption of coal and water for any output (kWh) per shift. The lines will cut the axis of coal or water above the zero point and will there show the minimum consumption of coal and water respectively required to keep the plant ready for service but with no kWh output at the bus bars. Once these lines are obtained the coal and water consumptions for each shift are compared with the 'standard' value for the kWh concerned. Unusually high coal consumption means that the boilers have been mismanaged, or that inferior coal has been used, or that steam has been wasted by blowing off, etc. In the latter event the point

* For a full explanation with examples *see* brochure on 'The Coal Consumption of Power Plants and Bonuses for Coal Saving,' by R. H. Parsons (*Electrical Review, Ltd.*).

plotted on the water chart will be above the normal line. The primary function of these charts is to call immediate attention to abnormal results so that they may subsequently be striven for if good or avoided if bad. If the general indication afforded by the charts is followed up by an intelligent search for causes of inefficiency, it will soon be possible to establish fresh standard lines corresponding to higher overall efficiency.

Useful suggestions for the compilation of statistical reports on a basis permitting direct comparison between different plants are given by W. S. Gorsuch, *Jour. Amer. I.E.E.*, Feb., 1920.

Comparison between the weight of water fed to boilers and the amount of steam fed to the main turbines (or the weight of condensate from the latter) leads to detection of excessive consumption in auxiliaries. Steam turbines should be tested over their full range of load every few months in order to detect deterioration of blading, etc.

193. Relative Importance of Efficiency in Various Parts of Plant.—The coal bill represents from 50-75 °/₀ of the total working costs (*i.e.* cost excluding capital charges) in most of the stations in Great Britain, hence reduction in the fuel consumption is one of the most valuable economies which can be effected. The importance of small differences in steam consumption of large generating sets, and certain risks attached to assessing the value thereof, are brought out by the following excerpt:—

A 10 000 kW turbo-generator loaded to an average of 7 500 kW for 8 000 hrs. per annum will supply 60 000 000 kWh per annum. A variation of 1 % in this output, on a coal cost of 0·15d. per kWh, equals £375 per annum, which is equivalent to £3 000 on an 8-year life. One set may consume 12·5 lbs. steam per kWh and cost £25 000. If a second set be offered, consuming only 11·5 lbs. per kWh (*i.e.* 8 % less), it is worth £24 000 more than the first set, but the actual difference in cost of manufacture will be no more than £2 000 or £3 000 [pre-war]. Naturally, substantial bonuses or penalties are offered or imposed for high or low steam consumption respectively. Large sums of money thus depend on the accuracy of test figures, which may be 3 % or 4 % in error, while the actual sums are often given in terms of one-tenth of a lb. of steam per kWh, *i.e.* less than 1 % of the total consumption (W. M. Selvey, *Jour. I.E.E.*, Vol. 53, p. 109).

It should be noted that the value of 1 % higher efficiency in any piece of apparatus varies with the actual efficiency of the latter. Doubling the efficiency of any step in the train of conversions between the coal pile and the bus bars would halve the coal bill for given kWh output; for example, the coal consumption / kWh would be halved by increasing the efficiency of

any piece of the apparatus from 10 to 20 %, from 20 to 40 %, or from 40 to 80 % but the increase in the percentage efficiency of the apparatus itself would be 10 %, 20%, and 40 % in the respective cases. This shows that 1 % increase in apparatus efficiency is more valuable the lower the initial efficiency (*see* col. 7, Table 24). On the other hand, the percentage gain in overall efficiency (reckoned from the coal pile) per 1 % increase in apparatus efficiency decreases with the energy input to the apparatus concerned (*see* col. 6, Table 24). For example, the input to the boiler (Table 24) is 100 B.Th.U., and increasing the boiler efficiency from 80 to 81 % results in 1 % higher overall efficiency and in $100 \, [1 - (80/81)] = 1{\cdot}25$ % saving in coal;* at the turbine the input is 79·2 B.Th.U., and the effect of raising the turbine efficiency from 27 % to 28 % is to raise the overall efficiency (coal to turbine shaft) by 0·8 %, but the saving in coal for equal output at the turbine shaft is $100 \, [1 - (27/28)] = 3{\cdot}5$ %.

TABLE 24.—*Approximate Distribution of Losses in an Electrical System and Relative Value of Efficiency Improvements.*

Apparatus.	Assumed Efficiency of Apparatus %.	Equivalent Heat Units.			Effect of 1 % Higher Apparatus Efficiency.	
		Input.	Lost.	Output (= overall Efficiency from Coal Pile).	Increase in Overall Efficiency from Coal Pile, %.	Saving in Coal Consumption for Equal Output, %.
Boiler	80	100	20	80	1·00	1·25
Steam pipes	99	80	0·8	79·2	0·80	1·00
Turbine	27	79·2	57·8	21·4	0·77	3·57
Alternator	95	21·4	1·1	20·3	0·24	1·05
Step-up transformer	98	20·3	0·4	19·9	0·20	1·01
H.T. mains	90	19·9	2·0	17·9	0·20	1·10
Step-down transformer	98	17·9	0·4	17·5	0·18	1·01
L.T. Cables	98	17·5	0·3	17·2	0·18	1·01
Motor	90	17·2	1·7	15·5	0·18	1·10

In choosing between alternative plants which may be available, the *loss* in each plant should be plotted to the same base as the load curve, the loss being calculated (for each load shown by the

* The saving in coal effected by increasing the efficiency of any apparatus from x % to y % is $100 \left(1 - \frac{x}{y}\right)$ %.

load curve) from the appropriate efficiency as shown on the load-efficiency curve of the plant. That plant which has the smaller total area below its daily loss curve will be the more efficient in the service concerned. It will be found that plant which has high efficiency at low loads will give particularly favourable results when the load factor (§ 261) is low (*see also* § 217).

194. Distribution of Generating Costs.—The cost of generating electricity may conveniently be divided into fixed charges (principally interest on capital, and depreciation) which do not vary greatly in total amount with the kWh output per annum, and working costs (principally for fuel) which increase roughly in proportion with the kWh output. The capital charges / kWh obviously decrease as the output increases, but the working costs / kWh vary little within a wide range of output. Table 25 (due to C. W. Charlesworth, Inc. Munic. El. Assoc., 1921) illustrates the composition of the total costs of electricity supply in average central stations. It may be stated, as a general rule, that where the load factor is high fuel economy is the prime consideration; the most expensive plant, with every refinement that will reduce the fuel bill, will be the best. On the other hand, where the load factor is poor, capital charges are of far greater importance, and a less expensive plant will give the lowest running charges.

TABLE 25.—*Composition of Total Costs of Electricity Supply.*

	Percentage of Total Cost in Year.		
	1913-14.	1916-17.	1919-20.
Capital charges	36	30	31
Fuel	25	40	35
Repairs, maintenance, water, stores, etc.	18	11	14
Shift and running wages	5	6	8
Local rates, management expenses, and salaries	16	13	12

An analysis of the distribution of working costs in typical central stations in Great Britain is given in Table 26. This is based upon data extracted from the Tables of Costs and Records published by the *Electrical Times*; the complete tables should be consulted.

TABLE 26.—*Analysis of Working Costs, etc., in British Central Stations.*

The figures given are the averages for six stations in each group calculated from figures given in the *Electrical Times* tables, November 2, 1922. It seems likely that these costs may be reduced by about 25 % during the period 1923-25 (*see also* Table 38, § 269).

Total kWh sold per annum	1 500 000-2 000 000	20 000 000-30 000 000	50 000 000-150 000 000
Plant capacity, kW	1 000-2 000	15 000-25 000	50 000-125 000
Working costs per kWh sold, pence :—			
Fuel	1·42	0·80	0·59
Oil, waste, water, and stores	0·15	0·02	0·02
Wages of workmen	0·46	0·17	0·16
Repairs and maintenance	0·56	0·22	0·22
Rent, rates, and taxes	0·19	0·15	0·18
Management, salaries, office and legal expenses, insurance, etc.	0·31	0·10	0·12
Total	3·11	1·47	1·31
kWh sold for private supply per head of population	45	113	117
Annual load factor *	20·1	20·2	21·5
Capital expenditure on whole system—			
£/kW connected	31·90	24·20	29·70
£/kW of station plant capacity	89·30	42·80	49·30

195. Capital Cost of Central Station Plant.—Under this heading little information can be given owing to the instability and abnormal level of post-war quotations. The figures in Table 27 will serve as a general guide, and for further information the reader should refer to the particulars of tenders published in the technical press. During the financial year 1920-21 the cost of equipment was generally from three to four times the pre-war price; in 1921-22 the factor was about 2-2½; and in 1922-23 about 1·75-2. It is probable that capital costs will gradually settle down to about 50 % above pre-war figures.

In *Power House Design* (first edition) Sir John Snell gave the (pre-war) costs shown to the left of Table 28 for a 25 000 kW Mond producer-gas plant, and the same authority (in his presidential address to the I.E.E. in 1914) gave the figures shown to the right of Table 28 as the minimum costs likely to be attainable in

* Calculated as (kWh sold per ann. × 100)/(max. simultaneous load on feeders in kW × hours of supply period) (*see also* § 261).

erecting a large turbo-driven central station at any time in the near future. At the time of writing (1923) the costs for the items in this table would be at least twice the figures shown.

Table 27. *Approximate Capital Costs of Power Plant Components.*

	Per	Pre-War.	Post-War, 1920-23.
		£	£
Horizontal return tubular boilers	Per 1 000 lbs. of water evaporated per hour into steam at a working pressure of 200 lbs. per sq. in. with 200° F. of superheat.	60-70	120
Water tube boilers, including integral superheater, and mechanical stokers with driving gear and accessories for the stokers		100-130	208
Lancashire boilers, hand fired, including superheater		100-150	210
Economisers for water tube boilers, per 1 000 lbs. evaporated per hour in the boilers under conditions stated in col. 2		20-25	47
Economisers for Lancashire boilers, per 1 000 lbs. evaporated per hour in the boilers under conditions stated in col. 2		30-40	64
Pipework for main steam, auxiliary steam, feed and blow down, including feed pumps but not including piping for exhaust steam and circulating water		30-40	55
Coal conveyors and overhead bunkers		40-50	97
Ash handling plant		15-20	34
Corliss engine, with piping and foundations	B.H.P.	5-8	9-14
,, ,, and generator	kW	13-15	22-25
Turbo alternators, 750-1 000 kW	kW	2	4-5
,, ,, 2 500-5 000 kW	kW	1	2-2·5
,, ,, 15 000-25 000 kW	kW	...	1·5
High speed steam engine and generator, 500-1 000 kW	kW	6-6·5	10-12
Gas engines, vertical, 150-1 000 B.H.P.	B.H.P.	4·5	7
,, ,, with generators, 500-2 500 kW	kW	5·5	8
Suction gas producers, 100-200 B.H.P.	B.H.P.	1·5	2·5
,, ,, ,, 200-1 000 B.H.P.	B.H.P.	1·25	2·0
,, ,, engines, 100-250 B.H.P.	B.H.P.	4·5-5	8-9
Gas producer plant with engines and generators complete, about 500 kW	kW	20-25	34-42
Diesel engine and generator, about 500 kW	kW	14-17	24-29
Semi-Diesel engine and generator, 50-200 kW	kW	16	28
Oil engine and generator, 10-30 kW	kW	25-30	40-50
Lightly built power house	kW	1·3	3
Substantially built (plain) power house	kW	2·5-4	5-10
Barometric condensers, 250-2 500 kW	kW	0·5-2	0·9-3·4
Surface condensers, with pumps, 250-1 000 kW	kW	1-2·5	1·7-4·2
,, ,, ,, ,, 10 000-25 000 kW	kW	0·5	0·85
Cooling towers, with fan	kW	1·5	2·5
,, ponds with spray nozzles, concrete basin	kW	0·75-1·5	1·3-2·5
,, ,, ,, ,, ,, puddled clay basin	kW	0·5-0·85	0·85-1·5
Transformers, 200-500 kVA	kVA	0·5-1·0	1·0-2·0
,, 1 000-2 000 kVA	kVA	0·4-0·8	0·75-1·5
Rotary converters, 500-1 000 kVA	kVA	2-3	5-8

TABLE 27 (*Continued*).

	Per	Pre-War.	Post-War, 1920-23.
		£	£
1 500 kW set of mercury rectifiers	kW	—	5-8
Switchgear for 1 500 kW turbo-alternator and rotary converter	kW	0·25-0·5	0·5-1·0
Switchgear for complete station, 5 000 kW upwards	kW	0·5-1·0	1-2
110-220 V generating set with switchboard and steam engine and boiler, *or* gas engine and producer, *or* oil engine . . . 5-10 kW	kW	50-75	85-130
20-25 kW	kW	30-40	50-70
Gas engine plant, 1 000-2 000 kW, without ammonia recovery, including generators, switchgear, and buildings	kW	15-20	25-35
Gas engine plant, 10 000-15 000 kW, with ammonia recovery, generators, switchgear, and buildings	kW	15-20	25-35
Complete steam-driven central station, including buildings, 10 000-100 000 kW	kW	8-15	25-30
Complete hydro-electric stations (*see* Table 35, § 216)	—	—	—
Substation, complete with transformers and converters, 2 000-5 000 kW	kW	4-7	7-12

TABLE 28.—*Pre-War Costs of Large Gas and Steam Plants.*

Mond Producer-gas Plant.	Per kW.	Modern Steam Turbine Plant.	Per kW.
	£		£
Slack handling, regenerator plant, and gas producer	1·06	Land, river walls, and sidings	0·25
Acid towers, recovery and sulphate plant	0·68	Buildings, coal silos, foundations, and cranes	2·00
Steam-raising plant and sundries	0·76	Boilers, economisers, coal and ash plant chimneys and mechanical draught	3·25
Gas engines and electrical plant (25 000 kW)	7·60	Turbo-generators, condensers, air filters, piping, tanks, and switchgear	2·65
Pipework, cooling towers, buildings and foundations	1·88		
	11·98		8·15

The capital cost of existing central stations in the United Kingdom, as represented by the total capital investment divided by the present kW capacity of plant installed, is very heavy in many cases. This is due to various causes, among which may be noted heavy legal and Parliamentary expenses, costly purchase of

vested interests, extravagance in original buildings, costliness of early electrical apparatus, failure to recognise and provide for the rapidity with which plant would become inadequate or obsolete, and failure or inability to meet from revenue all charges which should be thus met. In the past every central station scheme has had to start on a relatively small scale, and this has resulted in disproportionately heavy capital expenditure per kW; with interconnected stations and 'superstation' schemes this factor is not operative.

According to the *Electricity Commissioners' Report* (1921) the average capital expenditure in the United Kingdom on lands, buildings, sidings, wharves, etc., and generating plant (but excluding distribution items) up to December 31, 1918, was £22·2 per kW installed for public supply other than traction (*see* Table 29).

TABLE 29.—*Generating Plant Installed and Capital Expenditure for Public Supply (other than Traction) in the United Kingdom.*

Undertakings.		Generating Plant Installed.	Average Capital Expended on Lands, Buildings, Sidings, Wharves, etc., and Generating Plant, Excluding Distribution Items.
Class.	Number.		
Local Authorities—		kW	£/kW
London	14	131 791	25·6
Rest of Great Britain	214	1 290 133	20·3
Ireland	11	28 695	21·8
Total	239	1 450 619	20·9
Companies—			
London	15	216 037	29·1
Rest of Great Britain	162	135 645	31·8
Ireland	5	2 801	45·9
Total	182	354 483	30·2
Power Companies	17	370 053	19·6
Totals	438	2 175 155	22·2

Referred to the basis of load connected, the capital investment in existing English stations is often £25-£35 per kW in large

towns, and £40-£50 or more in small towns (*see also* Table 26, § 194); this figure gives the basis on which the fixed charge per kW demand should be estimated in framing tariffs (*see* § 272).

196. Power House Buildings; Space Occupied by Plant. —The main feature of modern central station buildings is their simple and economical construction; steel-framed structures of a strictly industrial type are employed; no expenditure is made upon purely architectural effects; and provision is made for easy extension. Ample supply of condensing water is indispensable in a steam turbine station, and in several instances shortage of water has made it necessary to go to other sites when additional generating plant was required. Cheap coal transport is also a primary consideration, and the question of ash disposal materially affects the selection of a site for a large station. The difference between, say, 5s. a ton and 6d. a ton to dispose of ashes (of which there may be 100-150 tons per million kWh) may exceed the capital charges on the additional transmission equipment required if the station be placed on the site where ash disposal is cheap.

The extended applications of electric power and the perfection of the steam turbine have led to rapid increase in the capacity of generating sets installed, till, in the latest 'big-unit' stations, there are, say, half a dozen turbo-alternators, each of 20 000 kW, 40 000 kW, or even greater power (§ 173).

The modern horizontal turbo-alternator occupies only [illegible] sq. ft. of floor area per kW, and it is quite a problem to accommodate the necessary boilers in convenient and efficient manner round a 'big-unit' power house. Adopting the most compact arrangement of boilers and coal silos, the ground space required is 4 or 5 times that occupied by the corresponding section of power house (including all auxiliaries and a fairly high percentage of gangway area), and 2 or 3 times that occupied by power plant and switchgear together. The largest horizontal turbo-alternators yet built (35 000-60 000 kW) occupy about 0·045 sq. ft. ground area and 0·72-0·82 cu. ft. overall space per kW. In a large-unit station, the total floor area required by power, switch, and boiler houses is about 0·6-0·75 sq. ft. per kW.

The Gennevilliers station of the Paris Union d'Électricité is of very compact design. The site of 11 hectares provides for extensions up to 320 000 kW total capacity; this will correspond to 5·94 or, say, 6 sq. ft. / kW. At the time of writing, the installed capacity is 200 000 kW, there being five 40 000 kW turbo-

alternators supplied by 25 boilers. The space occupied by the 200 000 kW equipment is approximately (per kW in each case): coal store 0·54 sq. ft.; boiler house 0·24 sq. ft.; machine room 0·12 sq. ft.; high-pressure switch house 0·17 sq. ft.; low-pressure switch house 0·032 sq. ft. From basement floor to roof, the boiler house and machine room are about 95 ft. high, and the switch houses about 50 ft. high.

The Gennevilliers station is described fully in a brochure published by *La Revue Industrielle* (Paris); see also *Engineer*, Vol. 134, pp. 242 *et seq.*

The Dalmarnock (Glasgow) station, with an initial installation of five 23 400 kVA turbo-alternators, and space available for extension to 200 000 kW total capacity, is described in *Modern Central Stations* by C. W. Marshall (Pitman) and in *El. Rev.*, Vol. 87, p. 324.

Modern practice is to use switchgear of the remote-control type, placed in a building distinct from the power house, and so constructed as to reduce fire risks to a minimum. Storage space for many thousand tons of coal is required, owing to the huge actual daily consumption of fuel and the importance of maintaining continuity of supply. Mechanical conveyers of various types are used to deliver coal to the boiler bunkers, the fuel being weighed automatically *en route*; and mechanical or pneumatic ash-handling plant is generally installed. The tendency is to use higher boiler draught (up to, say, 6 ins. water-gauge), produced mechanically, smoke stacks being reduced to the height required to carry fumes (there need be no smoke) clear of buildings.

197. Central Station Output.—The Electricity Commissioners publish annually statistics showing the total kWh per annum generated by stations in Great Britain; also, the number of stations in service, grouped according to the kWh generated. During the year ending March 31, 1921, 421 authorised undertakers in Great Britain generated, on the average, 10 400 000 kWh each, and 80 railway, tramway, and non-statutory undertakings generated, on the average, 9 800 000 kWh each. Of the 421 authorised undertakers submitting returns: 8·1 % generated less than 100 000 kWh during the year; 19·2 % generated between 100 000 and 500 000 kWh; 27·1 % between 500 000 and 2 500 000 kWh; 21·6 % between 2 500 000 and 10 000 000 kWh; 19·7 % between 10 000 000 and 50 000 000 kWh; and 4·3 % over 50 000 000 kWh. These figures do not include the many private generating stations for which no data are available.

The largest pre-war output in any one year from the whole of the public generating stations in the United Kingdom (about 500 in number) was roughly 2 000 million kWh. The electrical output in Sweden in 1914 (mainly from water

power) was about 1 475 million kWh, the population of Sweden being approximately 5 500 000 (32 per sq. ml.) compared with 45 400 000 (374 per sq. ml.) for the United Kingdom. During the war there was a striking development in this country in the application of electrical power to industry, chiefly in the manufacture of munitions, and the electrical output from public supply stations more than doubled in four years, amounting to 4 628 million kWh in 1918 (*Electricity Commissioners' Report*, 1921).

Now and in the near future one may take 200-250 kWh per head of population per annum (*not* per consumer) as the highest average consumption of electricity for lighting and power alone attainable in very large cities. Even this estimate is on the high side so far as Great Britain is concerned, 150-200 kWh *per capita* being a typical range for very highly developed electric supply areas. Traction loads may easily add 25 or 50 °/。 to these figures.* In large provincial towns 60-100 kWh *per capita* per annum is a good average for lighting and power consumption; and 20-30 kWh was the most that could be counted on in small towns when the demand was chiefly for lighting purposes, but, even in such places, electricity is now used for domestic and other small-power applications so that 25-40 kWh per head of population can be sold (*see also* Table 26, § 194).

198. Electricity Supply Legislation; National Organisation of Supply.—In the past the development of electricity supply in Great Britain has been retarded and restricted by the hopeless inefficiency (from the electrical standpoint) of the legislation which governed the industry for so many years, and partly perhaps by the fact that the average electrical engineer has taken little interest in this question. It should be obvious that every one engaged in the industry ought to have a knowledge of the man-made laws as well as the physical laws which govern his activities. The principal legislative measures concerning electricity supply in Great Britain are summarised in Chapter 41. The trend of these measures, as affecting the present position and future developments, is outlined clearly in the 'First Annual Report of the Electricity Commissioners,' which document should be consulted.

Under the Electricity (Supply) Act, 1919, the Electricity Commissioners are empowered, *inter alia*:—

* According to B. Welbourn the average consumption of electricity in Chicago is 714 kWh per citizen per annum, compared with 155 kWh in London, *including* traction demand in both cases (*Jour. I.E.E.*, Vol. 61, p. 31).

(i) To determine electricity districts, to approve or formulate schemes for improving the existing organisation for the supply of electricity in such districts, and to make Orders embodying such approved Schemes which may provide for the formation of Joint Electricity Authorities.

(ii) To consent or to refuse consent to the establishment of a new or the extension of an existing generating station or main transmission line, subject to certain provisos.

(iii) To require the alteration of the type of current, frequency or pressure employed in the undertakings of authorised undertakers, subject to certain provisos.

As pointed out by the Commissioners in their 'First Annual Report' the re-organisation of electricity supply in this country 'is not a question of starting, *ab initio*, to develop a comprehensive and standardised system of generation, transmission, and distribution on the basis of present-day knowledge and technical practice, as there already exists an extensive and heterogeneous development representing the uncoordinated growth of many years. The problem of reorganisation resolves itself into the determination of the best method of adapting, modifying, and expanding the existing development with the view of ensuring as speedily as possible an improvement in the supply of electricity for the numerous and growing needs of the community. It is only after thorough investigation at all stages, with full opportunity afforded to all interested parties to make representations at each stage, that a scheme for the reorganisation of supply in any district can become of statutory effect through the medium of an Order of the Commissioners, confirmed by the Minister of Transport and approved by Parliament.'

The provision made for the submission of schemes for improving the organisation of the supply of electricity in a district, and for safeguarding the interests of all parties concerned, is entirely to be commended provided that it is not abused by obstructionists.

A phase of electrical development which follows naturally from the treatment of electricity generation on a national basis, with widespread interconnected networks, is that of exporting electricity. Electricity has been transmitted satisfactorily from Sweden through a partly submarine cable (§ 292) to the Danish island of Zeeland for some years past, and schemes are in hand for a Norway-Sweden-Denmark transmission line which will make possible the utilisation of about 1 000 000 kW of water power at present going to waste. In Switzerland electricity is

exported during the spring and summer, and imported from foreign steam-driven stations when the native water-power is insufficient to meet the home requirements. At the time of writing, Canada exports nearly 1 000 million kWh per annum to the United States through a dozen transmission lines. Countries possessing surplus water-power will probably, in the near future, export electrical energy derived therefrom for distances up to 1 000 miles. There is much to be said for international electricity supply in preference to the export of coal.

199. Bibliography (*see* explanatory note, § 58).

Books.

Large Electric Power Stations. C. Klingenberg (Crosby Lockwood).
Steam Electric Power Plants. F. Koester (Constable).
Modern Central Stations. C. W. Marshall (Pitman).
Hydro-Electric Power Stations. D. B. Rushmore and E. A. Lof (Wiley).
Power House Design. Sir John F. C. Snell (Longmans).
Electric Power Systems. W. T. Taylor (Pitman).
Central Electrical Stations. C. H. Wordingham (Griffin).
The Steam-Engine and Other Heat-Engines. Sir J. A. Ewing (Cambridge University Press).

I.E.E. Papers.

Electricity Supply of Large Cities, G. Klingenberg. Vol. 52, p. 123.
Power Plant Testing, W. M. Selvey. Vol. 53, p. 109.
Coal and its Economical Use, P. S. Thompson. Vol. 53, p. 184.
Electricity Supply of Great Britain, E. T. Williams. Vol. 54, p. 581.
Thermal Efficiency of the Generation and Use of Gas and Electricity, Sir Dugald Clerk. Vol. 58, p. 765.
Utilisation of Exhaust Steam from Electric Generating Stations, C. I. Haden. Vol. 60, p. 265.
Utilisation of Waste Heat from Electrical Generating Stations, F. H. Whysall. Vol. 60, p. 271.
Interconnection of A.C. Power Stations, L. Romero and J. B. Palmer. Vol. 60, p. 287.

(*See also* Bibliography, § 184.)

CHAPTER 8.

WATER-POWER: GENERAL CONSIDERATIONS.

200. Wide Range of Water-power.—Although countries which had insufficient supplies of fuel have been developing their hydro-electric resources for many years, it is only recently that all civilised countries have undertaken systematic surveys of their available water-powers. At the present day experts in this branch of engineering are scarce, and even elementary knowledge of the subject is often lacking. It is only possible in this book to give a general outline of the subject, and specialist treatises must be consulted for details of hydraulic machinery and particulars of the civil engineering works involved in laying-out projects. These may comprise almost any conditions, from developing a 3-ft. fall on a river or canal up to that of a 5 000-ft. fall in a range of mountains; and from utilising the whole flow from the catchment area of a great river, such as the Mississippi, down to that from a few square miles of country with heavy seasonal monsoon rainfall. The power may be obtained from the normal flow of a river or canal alone; or from the same supplemented by storage; or (for the greater part of each year) from stored water alone. In every case water-power is the simplest example of power as represented by the rate of expenditure of ft.-lbs. per min.; in the old-fashioned overshot water wheel this was directly exemplified by each bucket carrying so many gallons of water and depositing it into a tailrace so many feet below the headrace. In hydro-electric practice the actual fall may be either a natural waterfall, or an artificial fall created by a dam or weir, or a fall developed by carrying the water along in a canal until sufficient drop has been accumulated above the original and more rapidly falling source.

201. Power Available from Water.—It is often assumed that an actual visible waterfall is necessary for the generation of power. In canals and in streams, where the slope of the bed

is extremely small, this is true, and power can only be generated where there happens to be an artificial fall (such as a lock or weir) or a rapid capable of being converted into a fall. On the other hand, the slope of rivers is generally greater, and an artificial head can often be obtained by carrying the water for some distance along a comparatively level artificial channel. The horse-power available in any case is, theoretically, the product of the weight of water in lbs. per sec. (*i.e.* cu. ft. per sec. × 62·3) multiplied by the vertical head in feet and divided by 550. The result must, however, be reduced in proportion to the inefficiency of the turbine or wheel, and the loss of head in the pipes, in order to find the actual B.H.P. available on the shaft. The efficiency of modern wheels varies from about 65 up to over 90 %, but for rough calculations and including pipe losses 80 % will not be far wrong. Taking this into account we have:—

Theoretical water H.P. = cu. ft. per sec. × head in ft. / 8·83.
Available B.H.P. = cu. ft. per sec. × head in ft. / 11.

A cu. ft. per sec. or 'cusec'—a useful irrigation term little known outside India—will therefore give 0·09 B.H.P. on the turbine shaft per ft. of fall; 0·9 B.H.P. per 10 ft. of fall; 9 B.H.P. per 100 ft.; and 90 B.H.P. per 1 000 ft. For rough project estimates the overall efficiency of medium-sized electric generators working at full load may be taken as 94 % (Chapter 10); if driven otherwise than directly off the turbine shaft there will be an additional loss of about 5 % in the drive. The electrical power available at the generator terminals, assuming this efficiency and converting from H.P. to kW, will then be approximately:—

For direct drive: Kilowatts = cusecs × head in ft. / 15·5 (say 15).
For indirect drive: Kilowatts = cusecs × head in ft. / 16·5 (say 16).

Thus, for example, we may have a canal fall of 10 ft. net with 1 000 cusecs flowing, or a mountain stream in which a fall of 1 000 ft. can be obtained with 10 cusecs flowing. In both cases: The theoretical H.P. is 10 000 × 62·3 / 550 = 1 150; the turbine B.H.P. is 10 000 / 11 = 910; and the electrical power is 10 000 / 15·5 or 16·5 = 645 or 605 kW, according as the drive is direct or indirect.

202. Constants and Approximations.—Table 30 and the

approximate relations given below will be found useful in dealing with water power. Explanations, where required, will follow in due course. Unnecessary decimals are omitted.

TABLE 30.—*Constants of Water.*

1 cu. ft. of water	= 6·23 Imp. gals. = 62·3 lbs.
	= 7·48 U.S. gals.
35·9 cu. ft. of water	= 1 English ton of 2 240 lbs.
35·31 " " " "	= 1 cu. metre.
1 acre-foot (*i.e.* 1 acre covered to a depth of 1 ft.)	= 43 560 cu. ft.
	= 1 223 cu. metres (m.^{3}).
22·96 acre-feet	= 1 million cu. ft.
1 sq. mile-foot	= 27·88 million cu. ft.

Flow of Water.

1 cusec or second-foot (*i.e.* 1 cu. ft. per sec.)	= 62·3 lbs. per sec.	= 0·028 3 m.^{3} per sec.
	= 3 738 " " min.	= 1·699 " " min.
	= 374 gals. per min.	
	= 86 400 cu. ft. per day	= 2 446 " " day.
	= 2·4 to 2·6 million cu. ft. per month.	
	= 31½ " " " " year	= 892 950 m.^{3} per year.

APPROXIMATIONS.—*Storage of Water.*

100 000 cu. ft. stored will give	1·16 cusecs	for 24 hrs.
	2¼ "	" 12 "
	4½ "	" 6 "
	9¼ "	" 3 "
	27¾ "	" 1 "

Thirty-one and a half million cu. ft. stored is equivalent to 1 cusec for a year; but owing to losses by evaporation, etc., the actual value is nearer ¾ cusec. The following approximations may be used:—

1 000 million cu. ft. stored will give	30 cusecs	for a year.
	40 "	" 9 months.
	60 "	" 6 "
	90 "	" 4 "
	120 "	" 3 "

Catchments.

A catchment area is the whole area (bounded by watersheds) draining into a river or stream at any particular point in its course. If the whole rainfall within a catchment reached the determined point in the stream (which is far from being the case), then:

1 in. of rain = 100 tons or 3 600 cu. ft. per acre,
= 64 000 tons or 2·33 million cu. ft. per sq. mile.

The actual flow-off is dealt with in § 204.

Power Available Under the Best Conditions.

(i) *From Flow—*

Cusecs × head in ft. / 11 = E.H.P. at generator.

" × " " " / 15 = kW " "

(On small projects and for average results divisors of 12 and 16 may be used.)

(ii) *From Storage—*

Thousands cu. ft. stored × head in ft. / 42 = E.H.P.-hours.

" " " × " " / 56 = kWh.

Millions cu. ft. stored × head in ft. / 370 = E.H.P.-years.

" " " × " " / 500 = kW-years.

" " " × " " × 17 = kWh.

203. Classification of Water-power.—Present-day practice tends to use only two types of prime mover for water-power, *viz.:* the Pelton wheel (jet impulse) turbine for 'high heads' and the Francis (reaction) turbine for 'low heads.' The range of the latter type is extending upwards, as Pelton wheels are not satisfactory except on heads of several hundred feet. There is a zone between the two extremes representing 'medium heads,' from about 100 or 150 ft. up to about 400 ft., but the modified types of jet impulse turbine, such as the Girard, originally in favour for this class of lay-out are now being superseded by the Francis type, suitably modified. Although, so far as the power plant and its utilisation are concerned, the difference may be only one of turbine rotors or runners, the actual development of sites for high, medium, and low falls offers considerable variety. Each is dealt with after considerations common to all have been explained.

204. Catchment Areas and Flow-off.—As the power available is always proportional to the product of flow and head or fall it follows that, whereas high-head plants can operate on a comparatively small flow, low-head plants of the same capacity require a very large volume of water. Except where great storage works are undertaken, nature fits in with these requirements; for while small individual streams in mountainous country, with small catchment areas, offer high-head developments, the great rivers into which they discharge supply the medium and low-head plants. From the point of view of hydro-electric works the absolute minimum flow of the source is the determining factor, except where water storage on a large scale is possible, as upon it depends the size of the plant that can be continuously operated. Where large-scale storage is possible, the minimum *annual* flow-off determines

the limits of the project, subject to the possibility of being able to carry over a reserve supply from a good year to a deficient one. The maximum flow-off in floods is necessarily always of importance in connection with the safety of headworks and dams and the provision of waste weirs or escapes or under-sluices for discharging the excess water.

Considering *small catchment areas* first, the flow from day to day in the streams fed by them evidently depends primarily on the amount of rainfall; but not *only* on the amount, as the rate or intensity at which the falls occur has a large bearing on the problem. Occasional showers are mostly lost by the way, in evaporation, or absorption by soil and vegetation. If the ground is dry, the first hours of rainfall may have but little effect on the stream; on the other hand, when the ground is already saturated, further rain will mostly run off to the stream. Here the nature of the ground has to be considered; bare steep rocky hillsides allow a very large proportion of rainfall to pass quickly down, while, at the other extreme, flat agricultural or forest land retains a large proportion of the fall and allows more to be lost by evaporation during its slower passage down. Then again, some of the rainfall sinks into the ground and reappears later in the form of springs; while high altitude snow, the most valuable form of 'white coal' to the water-power engineer, may supply a river with water at the time when the ordinary flow is at the lowest and during the driest of seasons. Where large scale storage of water is in question it is the minimum *annual* flow-off of the river that is of the greatest importance, but in the case of small, and probably high-elevation catchments it is the day-to-day flow-off and the maximum and minimum amounts of water arriving at the headworks of the project that matter most. For a full discussion of various empirical formulæ for obtaining the maximum flow-off from a catchment the reader is referred to Buckley's *Irrigation Pocket Book*, where actual results are also given of many known rivers. It will be sufficient here to mention Dickens' formula, *viz.*:—

$$D = CM^{2/3}$$

where D = maximum discharge, in cusecs.
C = coefficient.
M = catchment area, in sq. mls.

The author of this formula took C as 825 where the rainfall was

about 36 ins. a year and considered the same figure applicable from 24-50 ins. By actual application it has been found (*loc. cit.*) that the coefficient varies in Indian rivers from 120 up to 1 795. The former figure is for very large catchments with rainfall of the order mentioned; the latter figure is for small catchments with very heavy rainfall confined to a short season. Clearly in the case of small catchments a knowledge of the shape of the catchment—for its length will greatly affect the time taken by the water to reach a given point—of its steepness, of its cultivated area, and of the intensity of the rainfall, will help in arriving at an intelligent estimate. In obtaining the average flow, and to some extent the minimum, of a small catchment comparison with a neighbouring area where the flow has been measured may be of great value, the relative areas, configurations, and rainfalls being approximately known. Naturally a small catchment area is subject to very great variations in flow; for a heavy storm may sweep over the whole of it, just as a dry period affects the whole. To obtain reliable results it is of course far preferable to make actual measurements of the flow (§ 205) over as long a period as possible, for comparison with the rainfall from sufficient gauges in the catchment, and also for comparison with neighbouring catchments. The intervening watersheds may, however, affect the latter comparisons to no inconsiderable extent. In many countries regular gaugings have been taken for years in all promising catchments, either for ascertaining irrigation or power possibilities—the former generally on the larger rivers only.

When *large catchments* are in question it is clear that excesses and defects of rainfall will generally serve to make the limits of flow less extreme, though this is less true in countries subject to monsoon rainfall than elsewhere. In such catchments the annual flow-off in India is found to vary between 29 and 47 % of the total rainfall, except on the West coast where the rainfall is extraordinarily high. The whole question of the annual flow-off from a catchment is exhaustively discussed by Buckley in the work already cited. Where irrigation systems take off from large rivers the amount available below their headworks will naturally depend on the seasonal requirements, and the lower reaches may almost run dry; where, on the other hand, large scale storage is a part of the irrigation project, the impounding and regulation of flood waters may enable a far larger proportion of the total

annual flow to be utilised for power purposes on its way down than would happen with an untrained river.

Until recently the intensity at which rain falls has not been readily ascertained except by an observer with a stop-watch. It is true that approximations can be obtained from the curves of some self-recording clock gauges, but the cost of these precludes their general use and they do not register short periods of extreme intensity with any accuracy. The *fractionating rain gauge* recently described by one of the authors * will give the daily rainfall divided up into any required number of intensities, as accurately as the plain gauge gives the total, each fraction or intensity having its own collecting vessel. The principle employed is that of a fine jet with a number of leaping weirs. By an ingenious extension of the principle Mr. J. H. Field, of the Indian Meteorological Department, has also constructed a new type of recorder which, with a single tank collector, can be left for a whole season in a locality difficult of access and will then enable the total rainfall and the rates and times of fall to be tabulated with fair accuracy. The plain instrument has the advantage of being very cheap to construct, as the inventor has not patented it, and does not intend to do so. The device has been in use throughout a whole monsoon in Simla, recording rates up to 7 ins. per hour and amounts up to 5 ins. a day.

205. Discharge of Notches and Weirs.—A very full discussion of the various formulæ for flow in open channels, which follow, as well as of those relating to the discharge over weirs and through sluices and syphons, will be found in Buckley's *Irrigation Pocket Book;* while Garrett's *Hydraulic Tables and Diagrams for Practical Engineers* gives in addition discharge curves to meet every case likely to arise.

Triangular Notches.—For measuring small and variable discharges with accuracy the triangular notch is unequalled. The notch should be sharp-edged on the upstream side (or a thin plate of metal may be used) and in order to reduce the velocity of approach towards the weir the cross-section of the stream should be large in proportion to that at the notch. The general formula for a triangular notch is

$$Q = (4/15)\, CB\sqrt{2g} \times h^{3/2}$$

* 'An Automatic "Intensity" Rain Gauge without Clockwork,' by J. W. Meares, M.Inst. C.E.; paper No. 4 445, Inst. of Civil Engineers, 1923.

where Q represents cusecs, B is the breadth of the water flowing over the notch, and h the depth to the apex, both in *feet*. For a right-angled notch $C = 0{\cdot}59$ and $B = 2h$ so $Q = 2{\cdot}54\ h^{2{\cdot}5}$.

For example, take a depth of 6 in. or 0·5 ft. and the discharge will be

$$Q = 2{\cdot}54 \times 0{\cdot}5^{2{\cdot}5} \text{ cusecs}$$
$$= 2{\cdot}54 \times {\cdot}177 = 0{\cdot}45 \text{ cusecs}$$
$$= 27 \text{ cu. ft. per min.}$$

The above formula is also found in the form—

Gallons per min. $= 1{\cdot}91\ h^{2{\cdot}5}$ where h is in *inches*. In the same example this gives 168 gallons per min. which $= 0{\cdot}45$ cusecs.

The measurement of h is made a short distance upstream, so that the curvature over the fall does not vitiate the results; and while a foot rule placed on a carefully levelled post is often used a hook gauge gives more accurate results. This device consists of a sharp-pointed hook attached by a raising screw to a calibrated scale, such that the top of the submerged hook, when first touching the surface, indicates the depth h. In still water the moment when the upward moving hook breaks the surface can be judged with great accuracy; and where the water surface is likely to be ruffled the device is placed inside a pipe with a very small orifice opening to the stream, which ensures still water. The device is equally applicable in the case of water measurements for steam boilers, and gives a high level of accuracy.

Rectangular Weirs.—Where larger quantities of water have to be measured, sharp-edged rectangular weirs are used. These take two forms; first, where a straight weir is placed across the full width of a channel itself of rectangular section; and, second, where a complete rectangular notch, sharp-edged at both sides and bottom, is placed in a waterway of greater width, so that there are complete 'end contractions.' In the former case there will always be an appreciable velocity of approach, whereas in the latter this can generally be avoided. A further factor is that there should be a free drop below the weir; if the fall is submerged the discharge is decreased and requires different methods of calculation.

The fundamental equation for the discharge over a weir is—

$$Q = 0{\cdot}666 \times c \times l \times h\sqrt{2gh} = 5{\cdot}35\ clh^{3/2}$$

where
Q = cusecs.
l = length of weir, in ft.
h = height of water above crest, in ft.
c = a constant.

Taking an average value of 0·618 for c and keeping h in feet, the formula simplifies to the formula given by Molesworth, *viz.*:—

$$Q = 3{\cdot}31 \times l \times \sqrt{h^3}$$

while experimental values of c show that it varies from about 0·58 where h is large in proportion to l, and with complete end contractions, up to 0·65 with low values of h and suppressed end contractions. For the practical purposes of this chapter the latter formula is quite accurate enough, both with or without end contractions, so long as there is a *clear fall.*

For example, given a weir length of 5 ft. and a depth h of 6 ins. or 0·5 ft., the discharge will be

$$Q = 3{\cdot}31 \times 5 \times \sqrt{0{\cdot}125} = 5{\cdot}84 \text{ cusecs.}$$

Weirs with Velocity of Approach.—Where, however, there is a considerable velocity of approach to the weir this is equivalent to an addition to the 'head' over and above that of still water. This additional head in feet, H, corresponds to $H = \frac{u^2}{2g}$ where u is the velocity of approach in ft. per sec. This modifies the fundamental formula to

$$Q = 0{\cdot}666 \times c \times l\sqrt{2g}\{(h + H)^{3/2} - H^{3/2}\}$$

where the values of c are as already given.

Thus with the same data as in the last example, but with a velocity of approach of 6 ft. per sec. (taking the actual coefficient of 0·611) $H = 36 / 64{\cdot}4 = 0{\cdot}559$ and the discharge is

$$Q = 0{\cdot}666 \times 0{\cdot}611 \times 5 \times 8{\cdot}01\{(0{\cdot}5 + 0{\cdot}559)^{3/2} - 0{\cdot}559^{3/2}\} = 11 \text{ cusecs.}$$

Drowned Weirs.—When the surface of the tail waters is at a higher lever than the crest of the weir, so that the fall is to some extent submerged, the discharge is lowered; in this case

$$Q = cl\sqrt{2gh_1}(h_2 + \tfrac{2}{3}h_1)$$

where h_1 = the afflux, or the difference between the water levels up and down-stream of the weir, in ft.

h_2 = the height of the water surface down-stream above the crest of the weir, in ft.

c = a constant as before, of which 0·63 is the best average value for sharp-crested weirs.

For example, keeping to a length of 5 ft. and a depth h of 0·5 ft., let the afflux, h_1 be 0·3 ft. so that the weir crest is drowned by $h_2 = 0{\cdot}2$ ft.; then

$$Q = 0{\cdot}63 \times 5\sqrt{64{\cdot}4 \times 0{\cdot}3}(0{\cdot}2 + \tfrac{2}{3} \times 0{\cdot}3) = 5{\cdot}55 \text{ cusecs.}$$

In the similar example above, with no velocity of approach, the result was 5·84 cusecs with a constant of 0·618, so that to correspond strictly the above answer would be 5·44 cusecs. For rough work, therefore, a moderate degree of drowning may be ignored without serious error.

206. Discharge of Running Streams.—To ascertain the discharge of streams without using a weir, a fairly straight and level stretch must be found, and the channel made reasonably uniform for a certain distance (say from 25-100 ft.), according to the possibilities of the case. Careful cross-sections of the water are then made at the two extreme points and at several equal intervals between them, by measuring the depth at, say, 5 or 10 points on each cross-section. If the stream is of uniform width a mean cross-section can be plotted, by taking the mean of all the measures of depth in the centre, and similarly of all the measures at each other gauge point in the width; from this section, or directly from the individual areas, the mean cross-sectional area is worked out, and this multiplied by the *mean* velocity gives the discharge.

To ascertain the mean velocity floats are used. These should be put in some distance above the upper fixed point, and carefully timed in their passage over the selected length. Where the depth allows it, vertical floats, reaching almost to the bed-level, will give the *mean* velocity of the upper and lower surfaces near enough for practical purposes; but they should be sent down both sides of the channel and the centre in order that the average may give a true mean value. It will be found difficult to ensure this, as the floats will seldom keep a straight course for more than 10 ft. or so. Needless to say, if there are parts of the stream with no appreciable flow these should be omitted completely from both area and velocity calculations. Sometimes practically the whole flow is confined to a deep narrow channel in the centre or at the side. Where only surface floats can be used, the mean observed *central surface* velocity should be reduced by from 25 % up to 50 % in very small streams with rough beds; the actual factor by which the observed surface velocity should be multiplied is given in Table 31 (Unwin), according to the nature of the bed and the hydraulic mean depth (*see* R in Bazin's formula, § 210).

In general the seasonal variations in these streams are so great that what is really wanted is the minimum value of the flow, preferably in a dry season following a previous dry season.

TABLE 31.—*Multipliers for Mean Velocity of Water.*

Hydraulic Mean Depth.	Smooth Channels.	Rough Channels. Rubble Masonry.	Very Rough Channels. Channels in Earth.	Channels Obstructed with Detritus.
0·25	0·83 to 0·79	0·69	0·51	0·42
0·5	0·84 ,, 0·81	0·74	0·58	0·5
0·75	0·84 ,, 0·81	0·76	0·63	0·55
1	0·85	0·77	0·65	0·58
2	—	0·79	0·71	0·64
3	—	0·80	0·73	0·67
5	—	0·81	0·76	0·71
10	—	0·82	0·78	0·74
30	—	—	—	0·74

207. **Current Meters.**—Instead of obtaining the mean velocity of a stream by means of floats and a coefficient, modern American practice favours the use of current meters, which are similar to anemometers in design. These, when properly calibrated, give the actual velocity of flow at any point where they are used, with a very small error. In regular channels of reasonable depth very accurate results can be obtained by this means; the point of maximum velocity will then be on the centre line of the stream and at about one-quarter of the depth, and the proper coefficient can be applied to this maximum. It is higher than the surface velocity, and Grunsky * gives the coefficients shown in Table 32, where W / d is the width divided by the average depth of the stream.

TABLE 32.—*Grunsky's Coefficients.*

W / d.	Coefficient.
5	1·01
10	0·97
15	0·94
20	0·92
30	0·89
40	0·87
50	0·85
100 or more	0·82

* *Trans. Am. Soc. C.E.*, Vol. 66, p. 123.

The mean velocity in such regular channels is found on the centre line and at about two-thirds of the depth. It is preferable however, to take readings at a number of points and obtain the mean in that way. With irregular water courses the latter method is essential. In turbulent water the current meter is apt to give velocities and final results which are too high, sometimes to the extent of even 15 or 20 °/ₒ in large rivers; but in the like conditions float measurements will be equally inaccurate. Great care is needed in taking measurements by the current meter, as its axis must be kept correctly at right angles to the flow. In taking readings at, say, 10 points on the cross-section two methods are in vogue. In the one, the meter is slowly lowered at each point on the cross-section, at a uniform rate, allowed to remain for $\frac{1}{4}$ min. at the lowest point, and then slowly raised again. This gives a summation of the velocities on that vertical line. By the second method, readings are taken at 1/5 and 4/5 of the depth at each point and the mean result is taken as the mean for that point. For counting the revolutions of the vane accoustic arrangements, either mechanical or electrical, are preferable to visual observation and are generally used. For purposes of calibration, the meter is drawn through still water at a uniform rate.

208. Water Level Recorders and Hydrographs.—Whereever it is desirable to know the discharge of a river under very variable conditions, arrangements are made for observing or recording the height of the water at a point where careful cross-sections have been made. By means of actual gauging by one or other of the methods described the discharge is then calculated for various heights of water and a 'discharge curve' is plotted, with gauge heights as abscissæ and discharges as ordinates. Having established a correlation between the two, intermediate discharges can be read off the curve; and if the cross-section is measured for flood levels rising above the curve the latter enables a fair estimate to be made of the extraordinary discharges. Where it is not possible to have an observer always on the spot, an automatic 'water stage recorder' can be installed. In this the height is taken by means of a float in a still-water well connected to the river, and the results are recorded on a roll of record paper on a continuously revolving drum. The drum is actuated by a heavy weight and continuous records can be obtained up to six

months without attention, provided that the apparatus cannot be damaged by wild animals or interfered with by inquisitive visitors. Thus not only the maximum and minimum discharge and the discharge at any particular time can be determined, but also the total discharge over the whole or any shorter period. Where storage is involved this is of the utmost importance. The daily discharges in cusecs can also be plotted in the form of a hydrograph and, where the working head is known, power can be substituted for flow; similarly, the storage can be plotted in the form of horse-power hours.

209. Mass Curves.—If the rate of daily discharge of a river be known and recorded on a hydrograph or in tables a 'mass curve' of the river can be constructed. In this the abscissæ represent time, in days or weeks, and the ordinates represent the *total* cumulative amount of water that has passed the gauge.

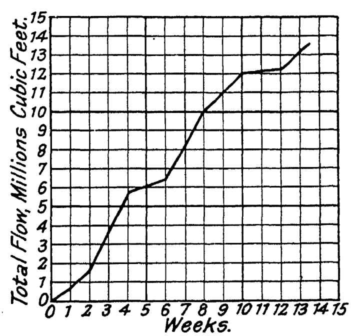


FIG. 48.—Mass curve for hypothetical stream.

Reducing matters to a simplicity which would not occur in practice, let it be assumed, for example, that a mass curve is constructed to begin on a certain date and that the discharge remains steadily at 100 cusecs for a week (Fig. 48), or that the mean discharge works out at this. Then at the end of that week practically 60 000 000 cu. ft. will have passed. If the discharge then rose to 150 cusecs and so remained for the next week a further 90 000 000 cu. ft. will pass and the total at the end of the second week will be 150 000 000; and so on. If the flow at any time practically ceased, as may happen in dry or monsoon countries, the curve would run horizontally for that time.

These curves are used in connection with storage projects, and weekly or even monthly averages are generally sufficient in plotting them; the slope of the curve at any point gives the rate of flow at that time; and the total flow up to any point, divided by the period in which it has flowed, gives the average rate of flow over that period. Clearly if the demand is greater than the supply at any time the balance must be taken from what has been stored. Where the mass curve has the most nearly horizontal slope the inflow is least; and this represents the greatest possible continuous power demand *without* storage. If the draft curve,

or line representing the average water drawn off, is plotted on the same paper with the mass curve the intervals between the two show when, and to what extent, the reservoir is being filled or emptied as the case may be.

The area and useful capacity of the reservoir in any particular case may be known; or it may be designed to meet the conditions disclosed by the mass curve. Similarly the amount of water drawn off from the reservoir for power may be known or the maximum which can safely be drawn off (allowance being made for evaporation) can be calculated from the readings of the curve. Thus the capacity of the stream, in conjunction with the storage for power purposes, can be fully investigated at the beginning; and the working conditions at any subsequent time can be obtained from the curves of inflow and outflow and the balance of useful water stored.

210. Bazin's Formula.—As a check on results obtained as in § 206, Bazin's formula may be applied to ascertain the mean velocity, namely: $V = c\sqrt{RS}$.

Where R = the hydraulic mean depth, or the area of cross-section of waterway divided by the wetted perimeter, *i.e.* the length of the wetted border in lineal feet; these factors can both be obtained from the cross-section.

S = the sine of the angle of inclination of the water surface, or the fall of that surface in a unit of length.

c = a coefficient, found from the formula $c = 157{\cdot}6 / (1 + m / \sqrt{R})$, the values of m being dependent on the nature of the channel, as in Table 33.

TABLE 33.—*Values of m in Bazin's Formula.*

Nature of Channel.	Value of m in Bazin's Formula.
Very smooth. Smooth cement, planed timber	0·109
Smooth. Planks, ashlar, bricks	0·29
Rough. Rubble masonry	0·83
Rougher. Earth newly dressed or pitched whole or part with stones	1·54
Very rough. Ordinary earth channels	2·36
Excessively rough. Channels encumbered with weeds and boulders	3·17

The slope in this case must be determined by precise levelling; and the converse case, where the slope of an artificial channel is

to be found from the remaining known factors, is the more usual application of the formula.

From a comparison of a number of formulæ quoted by Buckley (*Irrigation Pocket Book*), it would appear that the results given by Bazin's formula are decidedly low for small values of the hydraulic mean depth. A recent writer has suggested as a value for the coefficient above, $c = 117R^{0.26}$.

211. Size of Open Channel or Flume.—Bazin's formula in the preceding paragraph may be applied to the calculation of the size of an open channel for carrying a given quantity of water from a stream.

For example, suppose 20 cusecs are to be carried along a square or trapezoidal channel. Assume provisionally that a mean velocity of about $3\frac{1}{2}$ ft. per sec. will be used and the area of the cross-section must then be about $5\frac{3}{4}$ sq. ft. to give the required discharge. If the flume is rectangular in section and 3 ft. wide the depth of water will then be 1·9 ft.; the actual flume must of course be higher than this, as a margin against overflow is necessary.

The wetted perimeter will be $3 + 1{\cdot}9 + 1{\cdot}9 = 6{\cdot}8$ ft.

The hydraulic mean depth, R, will be $5{\cdot}7 / 6{\cdot}8 = 0{\cdot}84$.

If the flume is lined with cement the coefficient m will be 0·109; and the value of c will be $157{\cdot}6 / [1 + (0{\cdot}109 / \sqrt{0{\cdot}84}) = 141]$.

At this stage, if either the slope of the channel or the mean velocity is known, the other can be found.

Thus, keeping the velocity 3·5 ft. per sec., we have—

$v = c\sqrt{RS}$; $\therefore \sqrt{S} = v / c\sqrt{R}$ and $S = (v / c\sqrt{R})^2$,

i.e. $S = (3{\cdot}5 / 141 \times 0{\cdot}918)^2 = 0{\cdot}000\,74$ or, say, 1 in 1 400.

If the slope is given as 1 in 1 000, then—

$v = 141\sqrt{RS} = 141\sqrt{0{\cdot}84 \times 0{\cdot}001} = 4{\cdot}09$ ft. per sec.

212. Manning's Formula.—As a further check on the results obtained by Bazin's formula, whether used for calculating a discharge or for designing a flume or channel, Manning's formula may be employed, with the coefficients given in Table 34, *viz*:—

$$v = (1{\cdot}486 / n) \times \sqrt[3]{R^2}\sqrt{S},$$
$$\text{or, } S = v^2 n^2 / 2{\cdot}208\sqrt[3]{R^4}.$$

Taking the same example as in the last paragraph, *viz.* to find the velocity when the slope is 1 in 1 000, the coefficient of roughness n is 0·01 for smooth cemented surfaces and the velocity

$v = (1{\cdot}486 / 0{\cdot}01) \times \sqrt[3]{0{\cdot}705} \times \sqrt{0{\cdot}001} = 148{\cdot}6 \times 0{\cdot}89 \times 0{\cdot}032 = 4{\cdot}23$ ft. per sec.

213. Discharge of Sluices.—Where water flows through a *small* rectangular orifice with a free fall, and with a very low velocity of approach, the mean velocity through the orifice is

TABLE 34.—*Values of n in Manning's Formula.*

Nature of Channel.	Values of n in Manning's Formula
Smooth cement	[illegible]
Unplaned timber	[illegible]
Well-laid brickwork	[illegible]
Rough brickwork	[illegible]
Ditto, in inferior condition	[illegible]
Rubble masonry. Coarse brickwork	[illegible]
Canals in earth, and rivers according to condition	0·0[illegible]
Ditto, obstructed by detritus	[illegible]
Torrents encumbered with detritus	[illegible]

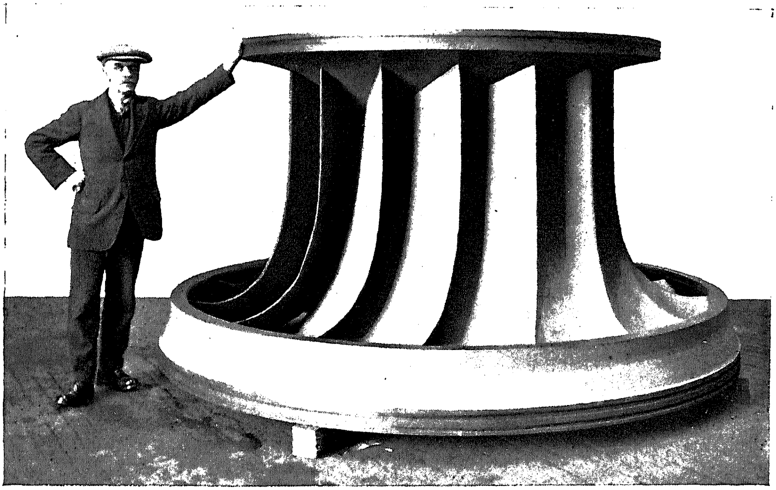
about $5\sqrt{H}$ ft. per sec., where H is the head in feet at the centre of the orifice; this expression is deduced from the fundamental formula $V = C\sqrt{(2gH)}$, the mean value of C being taken as 0·625. The discharge in cu. ft. per sec. is then the area of the orifice × the mean velocity. If there is appreciable velocity of approach, a less simple formula is required. If the orifice is submerged, the above relations hold good where H is the *difference* in height between the head and tail waters.

Where the head is small in comparison with the size of the orifice, the coefficient 5 in the mean velocity formula is too small; it may even be as high as 8 in some cases. The general formula in such cases may be taken as

$$V = 3{\cdot}3 \times \frac{h_2^{3/2} - h_1^{3/2}}{h_2 - h_1},$$

where h_1 is the head, in ft., at the top of the orifice
" h_2 " " " " bottom " "

214. Water Turbines in General.—For low and medium heads, pressure or reaction turbines are used, in which only a portion of the pressure and potential energy of the water is transformed into velocity and kinetic energy in the guide apparatus, the remainder being transformed in the turbine wheel. In these wheels the water is admitted round the whole periphery of the runner, at a speed lower than the spouting velocity due to the head. The speed can be varied within wide limits according to the design of the runner. The Francis turbine is the modern survivor of many types. The water may pass either radially inwards or outwards;



English Electric Co., Ltd.

A LOW-HEAD FRANCIS-TYPE RUNNER.

The runner illustrated is 10 ft. in diameter and weighs about 5½ tons. It absorbs 33 000 cu. ft. per min. under a head of 8·8 ft., and has a specific speed of 81 (British units); the power developed is 430 B.H.P. The plates are of thin sheet steel so as to give a large passage for the water and, in order to reduce the frictional losses to a minimum, they are ground and polished before being cast into the top and bottom rings. The edges of the blades are chamfered to reduce the losses due to shock at entrance.

English Electric Co., Ltd.

BUCKETS AND FASTENINGS OF A PELTON-TYPE IMPULSE WHEEL.

In the construction illustrated one bolt and one key hold each of the cast-steel buckets to the cast steel disc. The bolt carries the shear stresses, and the key bears the compression stresses. The bolt is tapered and fits inside a bush which is cylindrical outside and tapered inside. The bush and bolt are both provided with nuts, and the bush is split throughout its length, except at the threaded portion. On tightening the nuts, the bolt causes the bush to expand, and the locking washers are then bent over the lugs of the bucket and the faces of the nuts. The back of every alternate bucket bears against a fixed key dovetailed into and welded on to the disc. The two buckets between consecutive fixed keys are tightened by a pair of oppositely-tapered keys which, when driven home, are bent over on to the face of the disc thus forming, in effect, a single key.

[*To face p.* 315.

but the mixed flow turbine, which is the usual American form, is designed so that the water enters radially towards the shaft but leaves axially to the draft tube which utilises the suction head. The static pressure is 0·433 lb. per sq. in. per ft. of head.

For high heads impulse wheels (§ 253) are invariably used; in these the water is thrown on to the wheel from a nozzle at the full velocity due to the head. Here the casing is not filled with water, as in the former case, so a draft tube cannot be used. The form of the buckets is too well known to require description; the Doble form, in which a portion is cut away to allow the jet unimpeded access to where it can act most efficiently, is universally employed.

For a full discussion of the theory of these different types of turbines and their various subdivisions, the reader is referred to *Water Turbine Plant*, by Jens Orten-Böving, and other similar works. The theoretical velocity in ft. per sec. of the water issuing from a nozzle $= \sqrt{(2gH)}$, where g is the acceleration (32·2 ft. per sec.^{2}) due to gravity, and H is the net head in feet, *i.e.* the gross vertical head less the friction losses in the pipes (§ 247). Thus on 10 ft. head the theoretical velocity is 25·3 ft. per sec., on 100 ft. head it is 80 ft. per sec., and on 1 000 ft. head it is 253 ft. per sec.; the actual issuing velocity is less by about 3 %. The peripheral speed of an impulse wheel is a little less than half the theoretical velocity of the water, while in low-pressure wheels the speed can be varied within wide limits according to the design, as noted in dealing with variable heads.* Obviously, in either case, with a given head, the angular velocity will depend on the diameter of the wheel. It is often necessary, or advisable, to use two or four smaller wheels on a single shaft, instead of one large one, in order to increase the speed or reduce the cost of construction.

215. Specific Speed of Turbines.—In order to compare the performances of different turbines, and to utilise a standard design under varying conditions, a common basis is found in the 'specific speed' or the speed which would result if the wheel were reduced in exact geometrical proportion until it gave 1 H.P. under a head of 1 ft.—or, on the Continent, of 1 metre, though British units are used here.

* See also 'Run-Away Risks of Water Turbines,' P. Attlmayr. *Elek. u. Maschinenbau*, Vol. 40, p. 487; *Sc. Abstr.*, 304 B, 1923.

Rushmore and Lof define the specific speed as 'the number of revolutions per minute at the point of maximum efficiency that a homologous or geometrically similar wheel would give if it were to deliver 1 H.P. under unit head'—*Hydro-Electric Power Stations* (Wiley).

The specific speed should be as high as is practicable in reaction wheels working on low, and especially on variable low heads. Assuming a constant head and a wheel in which all parts and passages are of exactly the same relative proportions the velocity of the water will remain constant; in which case the quantity of water and the H.P. developed will vary as the square of the diameter, D, of the runner and the r.p.m. will vary as $1 / D$, whether the unit head h is taken as 1 ft. or as 1 metre:—

$$\text{Specific speed} = \text{r.p.m.} \times \sqrt{\text{H.P.}}/h^{5/4}.$$

If the head is expressed in metres (= ft. / 3·28) and the power in metric H.P. (= 0·986 British H.P.) the formula is of course unchanged, so the results expressed in metric specific speed are larger; thus:—

Metric specific speed = 4·38 × British specific speed.
British „ „ = 0·228 × Metric „ „

With more than one runner or nozzle the H.P. of a single one should be used. Pelton wheels have comparatively low specific speeds, varying from as low as 1 up to 6½ or 7 (British).

Thus in a particular instance, the head is 550 ft. and the 500 H.P. Pelton wheels work at 500 r.p.m. This gives

$$\text{Specific speed} = 500 \times \sqrt{500} / 550^{5/4}.$$

But $550^{5/4} = 550 \sqrt{\sqrt{550}} = 2\,660$

So specific speed $= 500 \times 23{\cdot}7 / 2\,660 = 4{\cdot}45$ in British units $= 4{\cdot}38 \times 4{\cdot}45 = 19{\cdot}5$ in metric units.

On the other hand, Francis wheels have much higher specific speeds, varying from as low as 20-30, on comparatively high heads of 400 ft. or more, up to several hundreds on very low heads. Efficiencies of 90 °/₀ have been obtained at all values from 25-90.

Thus a 500 H.P. reaction wheel working at 500 r.p.m. on a 50-ft. head would have a specific speed of $500 \times \sqrt{500} / 50^{5/4} = 84{\cdot}1$ or, in metric units, 368.

If any catalogue of small turbines is examined it will generally be found that the whole of the wheels in one series have the same specific speed, which is generally not stated in the case of British manufacturers.

Amongst recent advances the Kaplan and the Nagler wheels have specific speeds double those of other existing types, while further advances are foreshadowed (up to 1 600 metric), the efficiency in the former rising as high as 86 %.*

In the utilisation of low and variable heads these new runners should prove invaluable if performance under ordinary conditions confirms test results. As a high specific speed corresponds to a high actual speed in r.p.m. the size of direct coupled generators can be reduced, or direct coupling used where a geared drive would otherwise be necessary.

216. Cost of Water-power Plants.—It is difficult to give any reliable estimates of the cost of water-power development, as no two undertakings are alike. In a table given by Dawson, the *pre-war* capital outlay per H.P. ranges from £3 10s. to £84. Table 35 gives the capital cost (*pre-war*) of a number of hydro-electric developments in the East; the figures represent the total cost per kW capacity of everything up to the power station end of the transmission line.† Developments in mountainous country with heavy rainfall are generally subject to additional expense on account of landslips, where the ground has been cut away for open channels, etc. A substantial percentage should invariably be added to allow for this costly contingency. The prices of turbines given in makers' catalogues are useful as a general guide, but the turbine is a comparatively small item in the total cost, especially on high falls where a simple impulse wheel is used. In 1918, *Engineering* (Jan. 25, 1918, p. 100) gave as an approximation for wheels alone:—

For low heads, up to 25 ft., £4 per H.P.
,, high ,, ,, ,, 500 ,, £1 ,, ,,

but present-day (1923) prices are still well above these limits. The capital cost of a hydro-electric scheme is generally high compared with that of a steam or oil-driven plant; but the working expenses are lower and almost independent of the load (*cf.* § 194).

When any particular scheme has been designed, quotations

* *See also Science Abstracts*, Sect. B., Vol. 23, p. 332; Vol. 25, pp. 88, 229; and *El. Rev.*, Vol. 86, p. 466.

† The pre-war capital cost of hydraulic construction up to and at the power site, and of the power station and equipment averaged £14·40 in 70 representative Canadian hydro-electric stations, aggregating about 750 000 H.P. (*El. Wld.*, July 31, 1920, p. 230).

TABLE 35.—*Approximate Capital Cost of some Indian Hydro-Electric Developments.*

Head in Feet.	Plant Capacity. kW.	Approximate Capital Cost per kW.	Short Description.
High heads—		£	
1 000 to 1 800	30 000	25	Small average flow; large storage; no open channels.
	2 000	30	Small average flow; large storage; open channel.
	500	66	Small average flow; small storage; no open channels.
500 to 1 000	800	66	Moderate average flow; small storage; open channel.
	500	62	
	500	30	Small average flow; large storage; no open channels.
	50	73	
Medium heads—			
250 to 500	7 000	37	Large average flow; no storage; open channel.
	4 000	43	
	4 000	53	
	300	39	Small average flow; small storage open channel.
	150	49	
Low heads—			
6 to 30	500	60	Canal falls.
	450	20	
	250	42	
	200	100	

should be obtained from manufacturers or their agents for the turbines, generators, and regulating gear; the price (*pre-war*) may be anywhere between about £5 and £10 per kW, being higher for small sets and also for low heads. To this freight, carriage and erection must be added. High-class governors vary from £100-£300 each (*pre-war*), according to size and power. When estimating for buildings (§ 195), it must be remembered that plenty of space is essential, and that there must be ample head room for an overhead travelling crane to erect or dismantle the sets. Concrete work is always a heavy item, and must be carefully taken out in quantities; foundations, head and tail races, pentrough, sand traps, reservoirs, channels, etc., vary infinitely. The cost of the pipes and their freight and carriage to site can be estimated by the weight and cost per ton of steel work for the time being, and the ruling freights and cost of carriage; for size and thickness, *see* §§ 247, 248. Specials may

amount to about 10 % extra on the totals. The cost of making the pipe line and anchorages and erecting the pipes must be added, and no general figures for this can be given.

217. Economics of Steam and Water-Power.—In all cases of water-power large capital expenditure is necessary on the hydraulic development; furthermore, as water-power must be developed where it is found, a long transmission line is often necessary. For these reasons the total cost of construction is almost invariably higher than that of a steam-driven plant of the same capacity; and the annual capital charges for interest and depreciation are correspondingly higher.

Against this may be set the fact that the running costs of such a station are relatively low, as no fuel is involved. The total cost of running does not depend to any appreciable extent on whether the plant is fully or only lightly loaded; it is practically a fixed sum per annum; so that the cost *per unit* (kWh) is practically proportional to the total number of units generated. With fuel-consuming stations every extra unit generated involves the consumption of a definite amount of fuel with a definite cost; and while the *total* cost rises with the number of units generated and the cost *per unit* falls somewhat, the latter cost is by no means proportional to the total units. In any particular case, therefore, the practicability of a hydro-electric scheme depends on the cost of fuel in the locality where the power is wanted.

To take an example, assume a plant of 5 000 kW capacity is required at a certain place, where sufficient water-power exists within transmission distance, and that the total cost of the hydro-electric scheme and transmission line is £500 000. Taking interest and depreciation together at 10 %, the annual cost on this account will be £50 000. Let the cost of a steam plant of the same capacity, built where the power is actually needed, be assumed to be £150 000 with similar annual capital charges of £15 000. Now, if for simplicity it be assumed that the annual charges for wages, stores, repairs, and supervision are the same in both cases (an assumption near enough to the truth) there will be the difference between £50 000 and £15 000 or £35 000 to set off against the cost of fuel for steam raising. Under the ideal conditions of large electro-chemical works this plant, allowing 1 000 kW to be kept for spare, and, therefore, 4 000 kW for work, would generate about 28 000 000 kWh per annum (with 80 % load factor, § 261). Under ordinary industrial conditions the output would be less than half this, or, say, 12 000 000 kWh per annum. Clearly, therefore, not only the cost of coal but also the load factor of the plant or the ratio of its actual to its possible output is of immense importance. If it is assumed that the low amount of only 2 lbs. of coal will be required per unit, with modern plant of large size, the consumption would be 25 000 tons for 28 000 000 kWh, and 10 700 tons for 12 000 000 kWh. As the amount available to make the costs just balance out between steam and

water-power is £35 000, it follows that with the larger output, coal at £1·40 per ton would absorb this amount, while with the smaller output the figure would be nearly £3·27. From this example it will be inferred that as the load factor rises towards the ideal limit the advantage of hydro-electric power increases. Bearing in mind the vast rise in the cost of fuel at the present day the example is full of significance.

An interesting sidelight on the above discussion is also worthy of mention. The inexperienced financier is notoriously apt to look at present capital expenditure, and neglect to take into consideration future recurring costs; consequently, he often accepts the lowest tender to his ultimate detriment.

For instance, in the above example, it is assumed that a steam plant of 5 000 kW total capacity cost £150 000 and requires 2 lbs. of coal per unit. On the two total outputs assumed, the consumption of coal on this basis is 25 000 and 10 700 tons per annum. Would it pay to accept a tender of £120 000 for cheaper plant of the same output if the fuel consumption were then 2½ instead of 2 lbs. per kWh? The extra fuel used would amount to 6 250 and 2 675 tons in the two cases. Taking 10 °/₀ on the capital cost *saved* by accepting the lower tender, the annual saving is £3 000; the extra fuel used, even at £1 per ton, comes to about £6 000 with the large output of units and to about £2 700 with the lower output.

Thus with very cheap fuel and a 'bad load' it sometimes pays to buy comparatively uneconomical plant; but with expensive fuel and a good load factor *never*. If the cost of fuel assumed were £2 instead of £1 the more expensive plant would prove the cheaper on either the large or the small load in the example given. Much money has been wasted, and much disappointment caused, by the neglect of these principles.

In the matter of load factor an interesting contrast may be drawn between steam and water. No matter how ideal the conditions may be, every unit sold from a steam station costs a definite sum in fuel; and, therefore, even though some of the plant may be idle, there is an absolute limit to the charge per kWh below which sales would result in loss. Paradoxical though it may seem in view of all other commercial transactions, there is often practically no such limit in the case of a hydro-electric station: an exception being where the whole of the available energy can be sold without difficulty, owing to limitations of the available water. The total working costs are not affected by the generation and sale of additional units. Therefore, when all the load has been obtained that is in sight, at normal tariff rates, extra sales at any price will pay so long as they do not involve an

increase in the size of the plant. They bring in money without involving any expenditure.

For example, assume for simplicity, that a hydro-electric plant with a working capacity of 4 000 kW actually had this load during the whole working day from 6 A.M. till 6 P.M., but that for the remaining 12 hrs. its average load was only 1 000 kW, the average generating cost of a unit being ½d. under these conditions. If there were no prospect of obtaining work for the idle plant during these night hours on the ordinary tariffs it would pay to take on consumers at 0·3, or 0·2, or even 0·1d. per unit *provided* they were restricted to the use of power at night only.* Their additional consumption would bring down the average cost of a unit; thus, if night-working factories were started, using the whole available 3 000 kW, the average cost would be reduced from 0·5 to about 0·3d. per kWh; but in order to get the extra revenue it would pay to supply this factory at a far lower figure than the reduced average. It is, in fact, constantly done in actual commercial undertakings.

In considering the value of sites for industrial manufacturing work, one of the first points to consider is undoubtedly that of freight and carriage; for it has a triple application. In the first place, the raw material must be brought to the site, unless already on it; secondly, the finished product must be taken to its market; thirdly, the plant must be delivered at the power house. Cases are known where the carriage of plant over twenty miles of mountain roads abroad cost more than its freight from the land of manufacture to the railway terminus. Cheap power is useless if the saving is swallowed up in expensive freight. In order to get the plant to the power house there must be a road, and this road will generally be built so as to afford a suitable track for a railway. In the case of water-power from mountainous country there may be insuperable difficulties of ground or cost in laying out a railway to the site, though the plant can be transported there. Even if these difficulties do not exist, if the raw material of the industry is within the limits of transmission it will probably prove cheaper to erect a long transmission line rather than a railway, which may use more power than will be lost in transmission. It is simply a question of estimating which method gives the cheapest finished product. Either the material can be brought to the power house; or the power to the factory; or a combination of both methods may be the best.

Bibliography.—*See* § 258.

---

* It is assumed, as stated above, that there is sufficient water for continuous working at the higher output.

CHAPTER 9.

WATER-POWER (*contd.*): DEVELOPMENTS ON LOW AND MEDIUM HEADS.

218. Canal Falls.—Low-head hydro-electric installations are generally found either on irrigation canal falls or on rapids in rivers. In the case of canals the fall has generally been constructed primarily to alter the alignment of the canal from a higher to a lower level where the natural slope of the ground made this necessary; usually therefore the fall is fixed in height, subject to the variations due to the actual flow and to the rise of the tail waters. In these cases a power station can either be built across the canal itself or can be constructed at the side and connected by short diversions to the head and tail waters. The majority of such canals have falls of from 3-10 ft. or so, and turbines of the 'open-penstock' type, fixed on foundations in the water passage itself, are often used, the draft tubes either passing under the power house or discharging into a tail race tunnel which passes under the same.

On very low heads the width of the waterway may be insufficient to accommodate the wheels for developing the full power; if so, a short length of subsidiary canal can be constructed parallel to the main one, either on the upper or the lower level, and the power station built along the island between. In this way any length can be obtained to suit the number of generating sets. The subsidiary canal may be designed as a head race, taking off above the fall, in which case the tail waters discharge into the main canal; or the head race may be the canal itself, in which case the low level subsidiary canal tails the water back lower down.

Where two canal falls occur within a comparatively short distance it will probably pay to combine them into one. This may be done by a subsidiary head race or tail race canal, as above, or by a combination of the two. More rarely it is possible

either to raise the banks on the intervening stretch, so as to bring the whole fall to the lower point, or to lower the same and bring the whole fall to the upper point. The various methods are a matter of comparative capital costs.

Occasionally sites are found on irrigation systems where (as in the triple canal system of the Punjab) a canal takes off from one river and discharges into another, from which it is tapped again at some lower point. In such cases there may be a much more considerable fall, and the open-penstock system is replaced by a pipe system (§ 224).

A disadvantage of utilising canal falls is their liability to closure for annual repairs or because irrigation water is not required in the particular section involved. Continuity of supply is generally essential, so steam or oil reserve plant may be necessary, and it then becomes a question of estimates whether the double outlay is justified.

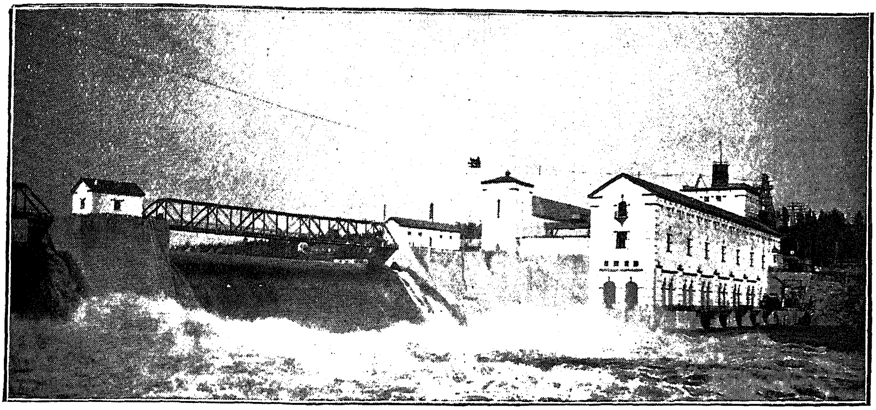
219. Low-head River Developments.—Probably the commonest form of hydro-electric development is where rapids on a river are concentrated into a single low fall by means of a 'lifting dam.' A good example of this form is found above Notodden in Norway, where there is a series of dams converting what was once a mighty torrent into a series of lakes, each delivering its quota of power from a power station at the artificial fall. In this particular instance there is the additional advantage, seldom obtainable, of a series of extensive natural lakes higher up in which the excess water from the mountains can be stored and regulated exactly as required.

Lifting dams vary from a few feet in height up to 100 ft. or more, according to the nature of the ground, and they may be of the gravity or arched type or hollow dams of reinforced concrete. The turbines are often placed in the dam itself, the water entering and discharging through it; with hollow dams the whole power house may be contained inside it. More often, the power station will be below the dam, the turbines being fed by pipes on the bank. Sometimes a short canal may even be necessary, leading to a forebay from which the turbines are supplied; especially, as mentioned in the preceding paragraph, where there would otherwise not be room for all the wheels. Yet again, there are instances where a tunnel has been made through the rock at the side and used (lined or not lined) in place of a pipe line.

In the case of low lifting dams, the storage above the dam is seldom sufficient to cope with more than the hour to hour variations of demand; if the water is drawn off faster than it flows in, the head is lowered and the capacity of the plant diminished. On medium heads (§ 225) this may be permissible. With low dams the surplus water is generally discharged over the crest of the dam itself. Arrangements have to be made for preventing debris, and especially floating timber, from entering the wheels in an open-penstock setting, or the pipes where these are used. In cold climates elaborate arrangements also have to be made for preventing ice from blocking up the water way or even forming in the wheels themselves. Both steam pipes and electrically heated grids have been employed for the purpose. Where timber flotation is carried on, or ice is found, it is desirable, if the lay-out admits it, to take off the water at right angles to the river; it is then easier to deflect the floating matter by means of booms and gratings so that the forebay is kept clear, but even so additional and finer screens are necessary to protect the intake to the wheels.

220. General Design of Low-fall Plants.—The head of water available in a low-fall plant is the vertical distance between the head and tail waters immediately above and below the wheel when running on full load; both the pressure head and the suction of a draft tube being utilised. On a fall of 8 ft. every inch represents 1 %, so it is necessary to ensure full size for both the head race and the tail race unless power is to be sacrificed; the velocity in these channels should not exceed 2 ft. per sec. If the depth of water over the turbine is insufficient, there is a danger of drawing in air and destroying the suction; about 5 ft. should be allowed when possible. A serious difficulty in low-head plants is the reduction in the working head which occurs from the backing-up of the tail waters in times of flood. In the Moody ejector turbine there is a connection from the water behind the dam to the draft tube, with gate control. When the head is reduced, water under the full head is thus allowed to enter the draft tube, increasing the velocity in it and compensating for the reduction due to change of level.* The depression below the 'standing wave' has also been utilised for the same purpose of

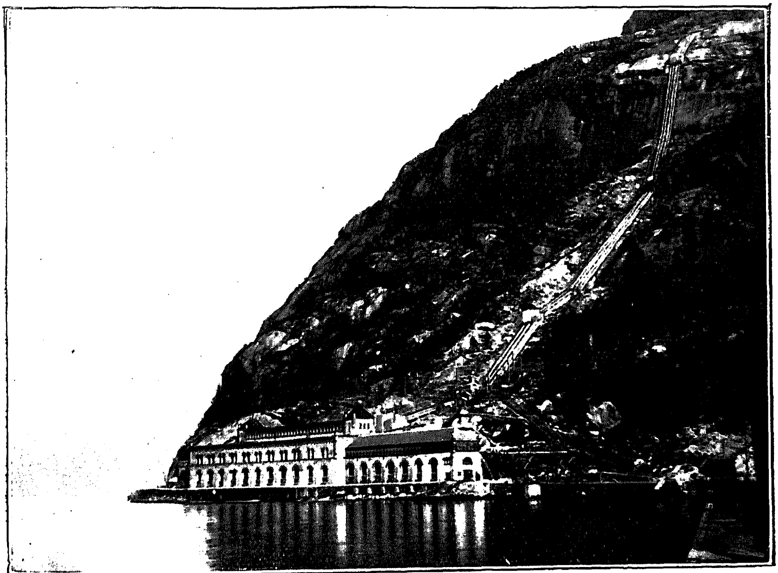
* *Science Abstracts*, *B*, 453 (1922) and 749 (1922).



Metropolitan-Vickers Electrical Co., Ltd.

BELOW-FALLS VIEW OF RAANAASFOSS LOW-HEAD POWER HOUSE AND DAM.

This 72 000 kVA station is arranged to utilise a minimum flow of 11 300 cusecs. For seven or eight months of the year the flow is 17 700 cusecs, and during floods it reaches 128 000 cusecs. The head on the turbines is $42\frac{1}{2}$ ft. Water from the turbines passes under the power house.

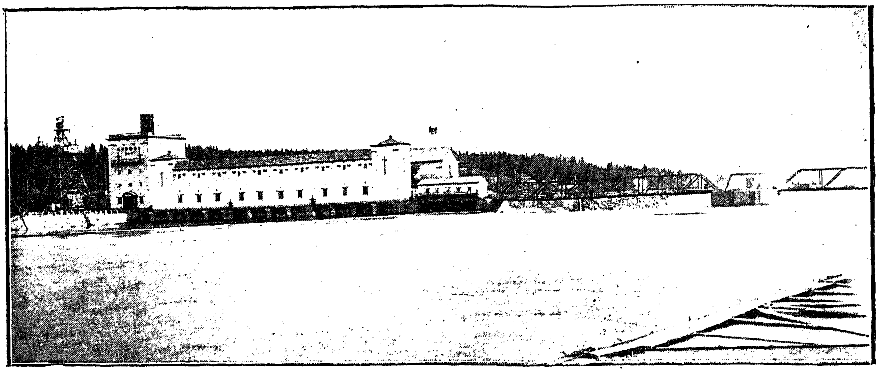


Metropolitan-Vickers Electrical Co., Ltd.

GENERAL VIEW OF TYSSEFALDENE HIGH-FALL POWER HOUSE AND PIPE-LINE.

This 117 000 kVA station utilises water from the 390 000 000 cu. yd. storage in Lake Ringadalsvand. The net head at the turbines is 1 260 ft. and, when this photograph was taken, there were four pipe lines, two feeding the turbines of seven 4 100 kVA generators, and two feeding the turbines of five 12 000 kVA sets. A fifth pipe, of 67 in., 59 in. and 49 in. inside diameters, feeds two 14 000 kVA sets.

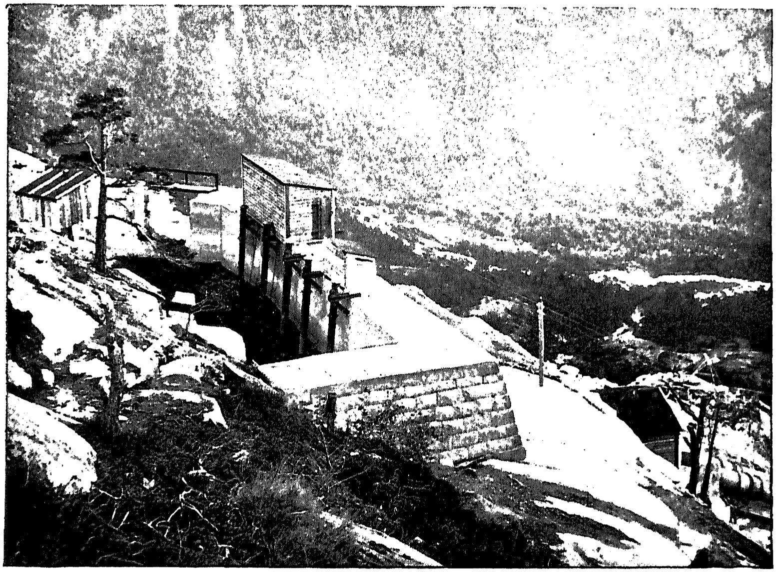
[*To face p.* 324.



Metropolitan-Vickers Electrical Co., Ltd.

ABOVE-FALLS VIEW OF RAANAASFOSS LOW-HEAD STATION.

The dam is divided into sections for regulating the river. There is an outlet for ice nearest the power house. Sluices, with sluice gates at the bottom of the dam, can take the whole flow during the winter if necessary. The sector regulating gates are not used during the winter and are protected against ice by wooden needle gates. There is a tubular gate in the dam at the end opposite from the power house.



Metropolitan-Vickers Electrical Co., Ltd.

INTAKE OF THE PIPE LINES SERVING TYSSEFALDENE HIGH-FALL STATION.

Water is brought to this intake from the storage lake by two parallel tunnels, each 3 700 yds. long and 97 sq. ft. in cross-section, cut through the mountain. Each turbine is arranged so that it can take water from either of two main pipes. There is a main sluice valve at the top of each pipe, and flap valves are also fitted which, in case ef emergency, can be operated by push buttons in the power house.

[To face p. 325.

compensation.* Both vertical and horizontal reaction wheels are used, and for very low falls they are generally placed directly in an open penstock or flume, and not cased in at all. The use of automatic generating stations to make profitable the utilisation of small streams with variable flow has been mentioned in § 187.

221. Low-fall Turbines and Regulation.—As already stated, the Francis type of wheel is mainly used on low falls, often with an open-penstock setting, up to heads of 60 or 70 ft. Frequently two or four runners are used on a single shaft, both with horizontal and vertical wheels, and even eight runners have been used on a horizontal turbine of this type; the number is determined by the power required, as on low heads the size of a single runner soon reaches practicable limits. The regulation of the entry of water is effected by gates actuated by the governor, and as lubrication can only be carried out when the wheel pit is emptied there is always a possibility of the mechanism sticking. The gates may be of three types, *viz.:* a cylinder gate moving parallel with the shaft; a 'register' gate, revolving so that the passages in it may be made to correspond or otherwise with fixed openings; or a pivoted series of wicket gates, actuated by a ring and crank so as to increase or decrease the water way.

222. Power on Low Heads; Water Used; Speed.—Owing to the low speed of turbines under very low heads, an indirect drive is always necessary, as the cost of direct-coupled generators would be prohibitive. We have then (§ 201)—

$$\text{kW} = \text{Cusecs} \times \text{Head} \,/\, 15{\cdot}5,$$

so that, for a 7 or 8 ft. head, the kW output will be about half the number of cusecs. Dealing with such a great volume of water as this means a large expenditure on excavations and foundations. According to the design of the blades, a considerable variety of speeds is possible without reducing the efficiency; for particulars of speed and output, manufacturers' catalogues must be consulted. In order to obtain a higher speed for a given output, double or quadruple wheels, mounted on a single shaft, are often used; the smaller diameter, with the same peripheral speed, gives a greater number of revolutions per minute.

223. Variable Heads.—In the case of low falls the working

* Professor Gibson in *El. Rev.*, Vol. 91, Nov. 17, 1922.

head often varies considerably. If the available quantity of water is much in excess of the demand, it may be convenient so to arrange the head and tail channels as to work always on the minimum head, the excess of head (when present) being sacrificed. This is not difficult to arrange in the diversion channels, by means of an adjustable weir in both head race and tail races. If the whole of the available power can be utilised, according to the head for the time being, then (*a*) the output of a given turbine varies directly as the square root of the cube of the head, (*b*) the normal speed varies directly as the square root of the head, and (*c*) the quantity of water used varies as the square root of the head also.

Thus, suppose a turbine giving 100 B.H.P. on a normal working head of 10 ft., running at 130 r.p.m. and using 109 cusecs. Then, if the same wheel is made to work on 5-ft. head,

$$\text{Output} = 100\sqrt{(5/10)^3} = 100\sqrt{0\cdot125} = 35\cdot4 \text{ B.H.P.}$$
$$\text{Speed} = 130\sqrt{(5/10)} = 130 \times 0\cdot71 = 92 \text{ r.p.m.}$$
$$\text{Quantity} = 109\sqrt{(5/10)} = 77 \text{ cusecs.}$$

A reference to any catalogue will show that these relations hold good, and the specific speed (§ 215) will be found to be 74 in both sets of conditions.

The actual speed in r.p.m. can be varied by making the diameter larger or smaller and also by varying the bucket design and the angle at which the water enters; thus for a given head and power the highest practicable speed may be six times the lowest.

Under great variations of head the voltage is maintained constant by shunt regulation and interpole generators; at Chester the working head varies from 2 to 9 ft. The use of two turbines on the same shaft is also sometimes adopted. There are some advantages in the use of vertical shaft Francis turbines geared to umbrella-type generators. Such turbines can be provided with a correctly formed suction tube for the utilisation of energy which would otherwise be lost, and the spiral inlet chamber makes possible higher inlet velocity than could be used with horizontal turbines. The generator may run at 10 or 12 times the turbine r.p.m. and can therefore be a relatively small and cheap machine. The vertical shaft permits the power house floor to be well above flood level, and the fact that the turbine and generator are not co-axial permits the turbine runner to be removed without disturbing the generator (*see also Science Abstracts*, Vol. 25 B, p. 581).

224. General Lay-out for Medium Falls.—The limits of a medium head of water are incapable of definition; low heads gradually merge into medium, and medium into high. It is often doubtful whether an open-type, low-fall turbine should or should not be used on heads of the order of 10 ft. and upwards, or whether an enclosed reaction turbine with a supply pipe will meet the needs of the case better. When dealing with heads where a supply pipe must necessarily be used, the question arises as to where an impulse wheel becomes preferable to a reaction turbine; probably the limit here will be in the neighbourhood of 300-400 ft.

As in the case of low falls, so long as the reaction type of wheel is used the 'head' is the vertical distance between the head and tail waters at full load, a draft tube being employed to utilise the suction head. When the jet impulse or Pelton wheel is employed the fall is classified as 'high head' (q.v.). There is an immense variety in the forms of hydraulic lay-out suitable for medium heads, some of these have already been discussed in connection with low heads, the difference being only one of degree; others follow.

225. Lifting Dam Lay-outs.—There is no reason, other than one of cost, why lifting dams should not be used, where the conditions are suitable, to give very considerable heads; but capital cost sets a limit. Where, however, this type of scheme is adopted the dam generally impounds a far greater quantity of water than with low heads while the draft, for given power, is reduced in proportion to the increase of head. It is therefore possible to use the ponded water to a much greater extent than with low heads, as a given drop in the water level means a far smaller percentage drop in the available head. Again, the volume of stored water corresponding to 1 ft. of depth near full supply level is very much greater than when the reservoir is partially empty; the lower depths give a comparatively small volume of 'dead' or unutilised water. If the head depends solely on the dam the maximum draw-off will be of the order of one-third of the depth, as beyond that regulation would become impracticable. In designing a scheme employing a lifting dam it is necessary to investigate the extent of the afflux of the water up-stream, in order to prevent the flooding of the surrounding country. Even when there is a fair bed slope the velocity of the stream is

checked and the waters bank up. A natural gorge has the same effect where a river has cut through hills.

For example, a site was investigated at Maheswar on the Narbada River in India, where there were rapids giving a fall of some 20 or 30 ft. in the dry weather; it was proposed to build a low-lifting dam and utilise the site. The river, however, had but little slope except at this one point, and it was found that a gorge about 100 miles down-stream had, about a century earlier, backed the water up no less than 63 ft. at the site, where the banks were high. The consequent afflux, even without the addition of a dam, probably flooded the flat country over thousands of square miles. The small head would in any case disappear completely, as in fact it was found to do in the monsoon; and the whole power station site would be under a great depth of water.

226. Natural Waterfalls.—Most natural waterfalls come under the category of medium head falls, but there is a considerable variety of ways of developing them. There must be an intake from the river above the fall into a forebay, protected as already explained in the case of low heads from the entry of floating debris. At the forebay there is an intake chamber for the pipes supplying the wheels, also protected by screens, and capable of being isolated in sections by gates in case repairs are necessary. The power station will generally be on the bank below the fall, and in favourable cases the length of pipe line will be short. The draft tubes will discharge into a tail race directly connected to the stream below the fall.

Special conditions, however, have been met by other arrangements. Thus several of the Niagara Falls power stations have deep vertical wheel pits containing the turbines, which discharge their tail waters through a tunnel; the wheels are connected by vertical shafts to the umbrella-type generators in the power house on the surface, and by vertical pipes to the forebay. In other cases the whole power station has been placed at the bottom of a vertical shaft in the rock, with a similar tail race tunnel, because no suitable site could be found for surface buildings.

227. Combination Falls.—Often the nature of the ground admits or demands additional works, such as head or tail canals and diversion dams. Thus, with a natural waterfall, additional head may often be obtainable by tapping the stream above rapids higher up than the fall itself and carrying an open channel or canal to a forebay at or beyond the fall. Similarly, rapids below the fall can be utilised by locating the power house farther downstream and using a canal to shorten the costly pipe line. Or,

again, a combination of these two variations may be employed. Low diversion dams across the river are often required to level up the bed above a waterfall and ensure the supply at low water reaching the intake. These will not necessarily increase the available head appreciably, for instance where a head canal is used; but they may sometimes be sufficiently high to act as lifting dams and to raise the forebay level. Again, where the head is primarily due to a lifting dam, the use of a canal may enable rapids lower down to be utilised. Naturally a canal can only be employed when the ground enables it to be constructed on a contour.

228. Bends in Rivers.—An occasional form of lay-out on medium heads is where a river makes a great bend and turns back on itself. If the bend has been caused by cutting through a range of hills there may be a considerable fall round it, and, by tunnelling through the intervening spur, this can be utilised for power.

A very good example of this type of lay-out (not yet developed) is found on the River Sutlej, where it emerges from the Himalayas, as reference to any ordinary atlas will show. Here an effective fall of some 300 ft. or more is obtainable with a minimum flow of about 3 000 cusecs (say 60 000 kW), which can be greatly increased if necessary by storage; and while the bend extends for many miles the tunnel and pipe line will be quite short.

This type of lay-out might even reach the 'high-head' level.

229. Storage on Medium Heads.—As a general rule artificial storage is impracticable until the 'high head' type of development is reached, and storage is therefore dealt with more fully in Chapter 10. Until a fairly great head is reached the quantity of stored water required to tide over any considerable period renders it impracticable. Reference has already been made to the use of the water ponded by a lifting dam; but this is little more than regulating storage, to enable a varying load to be met by a constant inflow of the source. If the quantity so stored is very large it may enable a period of drought to be surmounted; but this would seldom be practicable unless the ground was extraordinarily favourable. Such conditions may, however, occur where a large level basin can be formed into a lake by a comparatively low dam, and the rainfall and run-off enable it to be refilled periodically.

Thus a project is mentioned in the Second Report of the Hydro-Electric Survey of India, 1919-20, where it was proposed to use a storage of 7 000 million cu. ft. in conjunction with a fall of only 110 ft. in a locality when the rainfall is very precarious and the minimum flow small.

230. Storage and Tidal Power.—No doubt as fuel becomes more expensive tidal power may supplement other forms of hydro-electric and fuel-produced power, and projects are being examined at the present day.* For the most part such projects will be of low-head status, but it will be convenient to consider the matter briefly here, in connection with storage. The head obtainable by damming up a tidal estuary is an intermittent one; as the tide rises, its level will reach that of the water above the dam; furthermore, it is widely variable between spring and neap tides. Only where an enormous volume of water can be stored is there an economic possibility of obtaining power on a large scale, and then it is essential to make that power continuous; the natural conditions for large storage are, however, more often found in estuaries than on dry land. In order to continue generating power during the period when the tidal head disappears it is necessary to install reserve plant. This may be fuel driven; but an alternative exists where there are natural storage sites at a considerably higher level than the tidal basin itself. In such a case, part of the tidal power can be set aside exclusively to pump water to the higher-level basins,† from which it can flow down through the turbines of the reserve plant when needed. This arrangement is expensive in capital cost, as it involves double sets of plant and great expenditure on storage works; it is also uneconomical, as a large part of the initial power is subject to double conversion losses; but it may hereafter be rendered necessary owing to the increasing cost of other forms of power. It may be possible in some instances to utilise the high spring tides to fill high level basins, which can be kept in reserve to supplement the reduced power at times of neap tide; but the amount of storage required to carry over a large power station for a week or so on a comparatively small head will

* For particulars of the proposed Severn barrage see *El. Rev.*, Vol. 87, pp. 762, 788.

† Naturally if the high level basin can be filled without the use of power from the plant it is advantageous. In this connection there are possibilities in the 'Hydrautomat' which utilises a fall for raising a portion of the water with exceptionally high efficiency and low cost.

always render the problem a difficult one of economics and finance.

231. Canals and Forebays for Medium Heads.—Medium falls will generally be obtained from rivers, and according to whether there is an actual waterfall or merely a series of rapids, there may be a short or a long canal or flume leading to the forebay from which the pressure pipes take off. In the former case it may sometimes be practicable to build the forebay directly on the up-stream side of the fall, and to dispense with a canal altogether. Formulæ for calculating the size of flumes and canals are given in §§ 211 *et seq.;* if the quantity of water is considerable, an ordinary earthwork canal will be used, puddled if the ground renders it necessary; other types of channel are dealt with in Chapter 10. The water will be led into a forebay, from which the pressure pipes will be taken off. The supply at this point will be controlled by valves or gates, and an overflow and scour must be provided. As a rule nothing in the way of silt traps (§ 238) will be required with fairly large discharges, but strainers are necessary for catching weeds and other floating matter; a coarse 'trash rack' should be placed at the intake to protect the channel, and a finer one in the forebay, close to the gates, to protect the wheels. The usual arrangement is to have a separate intake chamber for each pipe, controlled by gates and screens, but open to the air at the top although protected there from the entry of foreign matter. This ensures that under no circumstances can a pipe collapse from external air pressure, and enables repairs to be effected easily. The capacity of the forebay needs careful consideration where any length of canal intervenes; generally a canal on a plant of this nature is kept always full, and a spill-way is constructed at the forebay so that in case of reduction of load the excess water can pass away over it; if, however, there is a necessity for economising water, as will be the case when storage is depended on, it is necessary to regulate the water at the canal intake. There must then be sufficient water stored in the forebay to enable a sudden rise of load to be coped with until the canal flow can be increased and can reach the forebay. Often it is convenient to have a long spill-way at or near the canal intake, so that when water is plentiful an excess may be always entering and when the afflux reaches the spill-way level no further appreciable rise can occur.

232. Pipes for Medium Falls.—Where the conditions are such that an open wheel in a flume cannot be employed, the water is piped down to a cased-in wheel, and a draft tube leads into the tail race. The velocity of the water in the supply pipe, if short and on a moderate head, may be as high as $0{\cdot}1\sqrt{(2gH)}$, giving 3·6 ft. per sec. for 20 ft.; 5·1 ft. per sec. for 40 ft.; and 7·2 ft. per sec. for 80 ft. Whether these maximum velocities can be realised, depends on the conditions in each case. The size of pipes and the loss of head in them under different conditions is dealt with more conveniently in connection with high heads (§ 247). As regards the thickness of metal in steel pipes (§ 248) on comparatively low heads, the result of the ordinary calculations may give too low a result for mechanical reasons. The author once saw a very large pipe (about 12 ft. diameter) on a head of about 50 ft. which had collapsed inwards; the water had been let out through the draft tube when the gate at the top was closed, so that practically the full atmospheric pressure of 14 lbs. to the sq. in. was acting upon the upper part. The pipe was more than strong enough to resist the internal water pressure, but this contingency had been overlooked. The draft tube, which on very low falls is usually a matter of 2 or 3 ft. only, may theoretically have a suction of nearly 30 ft., but in practice it should seldom exceed 20 ft.; even so, unless perfectly air-tight, there will be a loss of efficiency. At high elevations, with the barometer standing at 22 or 23 ins., the suction must be reduced proportionally, as well as in very large pipes.

Where the slope of the pipe line or part of the same, on a medium head, is very gradual a stand pipe or surge tank may be necessary at the power house or at the end of the flatter portion. This will be of the full diameter of the pipe protected and will be enlarged at the top, so as to act as a regulator while the velocity of the water is adjusting itself to new load conditions; this stand pipe will be carried above forebay level and will act as a subsidiary forebay closer to the turbines, storing or surplussing water when the draft is checked and supplying it while the long column of water in the pipe is accelerating. Thus the speed of the wheels is kept more nearly constant as the effective head varies but little; and the larger the surface of the water at the top of the surge tower the less will the variation be. In addition to the simple type of stand pipe there is a differential

type, consisting of a plain vertical stand pipe surrounded by a storage tank of larger dimensions, connected to it by inlets of restricted size. Here, if it be assumed that there is a steady load, the water in the inner and outer compartments will be at the same level. If now load is thrown off, the check to the flow causes the water in the plain stand pipe to rise to a higher level than that in the outer tank, into which it will discharge; but, as the passages are restricted, the level in the outer tank will take some time to rise to the new level, according to the difference of head. If, on the other hand, extra load were thrown on, the stand pipe would at once respond to the demand and fall in level, while the outer tank, now standing at a higher level, would refill the stand pipe at a rate corresponding to the difference in head. The design of surge tanks is a complicated matter which would be out of place in this volume (*see* Bibliography, § 258).

233. **Turbines for Medium Heads.**—As in the case of low heads, the Francis type of wheel is most generally used on medium heads; but it is of the cased-in type, supplied by a pipe and discharging through a draft tube. The most usual form is the 'spiral-cased' wheel, in which the water passes into the wheel all round the periphery, by means of a passage graduated to suit the diminishing volume of flow as water is taken off through the guide blades. The pipes may enter either at the end of the wheel, parallel with the shaft, or at the side and at right angles to the shaft. The wheels may be classified, according to the direction of flow of the water in them, as inward-flow, outward-flow, parallel-flow, or mixed-flow, the latter being the most generally used. In this last-named type the guide blades are placed round the outside of the wheel and the water, entering at the periphery, flows towards the shaft as in an inward-flow wheel; then the direction changes to that parallel with the shaft and so discharges into the draft tube. The guide vanes themselves are hinged and used as the wicket gate for regulation.

As mentioned in § 215, new types of reaction wheels for low and medium heads, with high specific speeds, are now being introduced and may considerably modify future practice.

For small powers, impulse wheels of different type from the Pelton wheel were at one time extensively used, such as the Girard, which has done good service. In this type the water from a rectangular jet emerged at the full velocity due to the

head and struck the curved vanes; the water passed radially outwards from the jet, which was placed between the shaft and the periphery.

Recently the Banki turbine, an entirely novel type of impulse wheel, has been placed on the market for fairly small powers. This is a modification of the old Poncelet wheel, differing from it in that the buckets of what is practically an undershot water wheel are open at the back instead of closed. The water, entering with the velocity due to the head, passes through the forward set of curved vanes; in doing so, it delivers up about 78 °/。 of its theoretical power but still continues to travel with considerable velocity. The water, now travelling across the inside of the wheel, in a direction slightly upwards, then strikes the buckets on the opposite of the wheel from the inside, in the reverse direction, and delivers up the practicable remainder of its power. The wheels are cylinders with the length up to twice the diameter, and the curved vanes run parallel with the shaft; the jet is rectangular and of the full length of the wheel, the breadth being regulated by a plain gate which reduces the breadth of the jet over its whole extent; a deflector is also employed to surplus the water at partial gate opening. As in other impulse wheels, the peripheral speed is limited to a little less than half the jet velocity, or $\frac{1}{2}\sqrt{(2gH)}$; on low heads it is therefore necessary to drive the generator indirectly. The specific speed (British units) of single runners is intermediate between that of the Pelton wheel (say 1-7) and the Francis wheel (say 25-90), varying from about 11 on moderate heads up to 25 on low heads; it is stated by the makers to be 119 metric ($=27{\cdot}2$ British) where the breadth is twice the diameter, and can be increased to double these values with four runners.

Bibliography (*see* § 258).

CHAPTER 10.

WATER-POWER (*contd.*): DEVELOPMENT OF HIGH FALLS.

234. Conditions of High-fall Development.—As in the low and medium falls already examined, there is a great variety of type in high-fall developments. Broadly, two divisions may be considered, *viz.:* projects depending primarily on *flow* and those depending primarily on *storage;* but combinations of the two are also common. In this connection a clear distinction must be drawn between *regulating storage*, adopted for taking care of day to day or possibly week to week fluctuations of load, and *main storage*, designed to carry the entire load for extended periods. A high working head can generally be obtained only from the flow of hill streams or the stored water of mountain catchments. The fall is generally obtained by leading off the water in an open canal or artificial channel, with a small slope, until it has reached a point where the accumulated fall is sufficient; there the forebay is constructed and steel pipes convey the water to the wheels. Occasionally sufficient fall can be obtained on the spot to enable the canal to be dispensed with, the pipes being led directly down to the power house from a forebay at the source; this is naturally cheaper in cost and preferable when the ground admits of it.

235. High-fall Projects Depending Mainly on Flow.—Where a hill river or stream has a reasonably high minimum flow and a steep descent, the limit of fall obtainable depends mainly on the distance to which the banks allow a contour canal to be constructed. When the limits of the canal are reached, or at an earlier point if the required fall has been obtained, the forebay is laid down from which the supply to the wheels is taken by pipes. If possible a large forebay or an independent regulating reservoir is a useful addition as it enables a fluctuating load to be dealt with, larger than the stream is capable of supplying continuously.

The canal may be on either bank of the stream or may be

carried by means of a tunnel through the hillside to a neighbouring stream, where a greater fall is obtainable; the canal can also be continued in this new catchment, and it may be practicable to lead the waters of it into the canal also. Sometimes several streams can in this way be harnessed together, either by open contour channels alone, or in combination with tunnels, syphons, and even suspension aqueducts.

In hill streams the normal flow is generally clear and moderate or small in amount; after heavy rain the discharge is increased many hundred fold, and the high velocity may cause it to carry along a large amount of mud, gravel, and boulders. These, despite various methods of trapping them, will inevitably tend to block up the channel and reach the forebay and the wheels, so that it may be advisable during spates to close the head-works gates; but this can only be done where sufficient storage is carried to tide over the worst period, and the problem offers much scope for ingenuity in the designer. Occasionally a high fall can be obtained from a comparatively sluggish stream, or one with a natural lake regulating its flow and clearing its waters, when the problem is simplified. By means of a dam in the stream itself it may be possible to reproduce these natural conditions, but there is always the possible silting up of this artificial lake to be reckoned with. If the water is seldom silt-laden the storage obtained in this way may be most valuable for regulating purposes.

236. **Head-works.**—No two streams require the same treatment at the head-works, where the water is tapped off. If the stream is a comparatively sluggish one, and the ground is suitable, water may be impounded in the stream bed itself by a dam; this will be cheaper than an excavated reservoir in proportion to the amount of water stored. In such a case it may sometimes be practicable to pipe the supply straight from the reservoir, putting in valves and strainers there. Unless the site is abnormally favourable, however, it is useless to build a dam for storage purposes if the debris brought down the stream is considerable, as the capacity will be rapidly reduced. In the case of torrents, if the bed at the head-works site is rock which can be depended upon, an inexpensive diversion into the flume will serve as well as anything; a gang of labourers can ensure continuity of supply. If the bed is not of solid rock it is liable to be scoured out and to drop perhaps 20 ft.; in such cases the flume proper should begin

at a somewhat lower level than the point of tapping, so that, whatever happens, it will always be possible to lead the water into it. The loss of 20 ft. of head can perhaps be ill spared, but it is obviously safer to lose it rather than to find the flume high and dry above the remains of the head-works. So long as no such catastrophe occurs the spare head can be disposed of by discharging down a series of steps.

In some cases, following irrigation practice in canal protective works, protection against scour has been sought by means of boulder-crates, sunk deep down and continued up to the surface level; these are made up of heavy-gauge galvanised iron wire, threaded into a large-mesh cubical box, and filled with large stones. The chief advantages of these crates over masonry are that they can easily be unloaded and moved when necessary, and that they are not readily destroyed by the impact of boulders. The less masonry is employed at the head-works of mountain torrents, the more likely are the works to stand; until the flume is well above flood-level, it cannot be considered safe from destruction in flood times, and at this point there should be a by-pass back to the stream. The gates controlling the entrance to the flume should preferably be rough and inexpensive; valves stand a very good chance of sticking after a few weeks owing to mud and debris choking them.

237. Open Channels.—Assuming that some distance intervenes between the head-works and power house, an open channel is generally preferable to pipe-work for conveying the water to a point above the station. The object of the channel is to convey the required quantity of water to the forebay with as little loss of head as possible. If the quantity is very large and the ground suitable a canal in earth will be used; but in the hills the conditions are adverse to this. There remain rectangular wooden flumes and semicircular iron channels, carried on trestles, both of which are very largely used in America; also concrete flumes, and, for very small discharges, even galvanised iron flumes.

In calculating the size and slope of the flume the formula given in §§ 210, 211 may be used, as in the example there given, preliminary data being assumed. The trapezoidal or semicircular shape will generally be the best, as these give a larger hydraulic mean depth (§ 210) than a rectangular section of the same area. In constructing a flume, it is well to remember that a very slight

error in the slope may either bank the water up and cause it to overflow or may increase the velocity sufficiently to wear away the material rapidly. Furthermore, at all angles in the direction of flow the friction is increased, and either the area or the slope should be increased accordingly and the afflux calculated. When in work there is always a danger of a flume becoming blocked by landslips, and the consequent overflow may wash away the track on which it is placed. To minimise the effects of this, the top levels should be varied in such a way that if the water overflows it will do so where the ground will stand it; with slopes of the order of 1 in 1 000 a slight raising of the height of the flume walls at all dangerous points will ensure this. Furthermore, at convenient points, *e.g.* where crossing small streams, the bed of the flume should be dropped and a gate put in, capable of diverting the whole flow back into the main stream. It is evident that, on steep ground, cutting away the hillside should be reduced to a minimum; a wooden or iron flume can be carried along on supports without appreciably disturbing the ground. Where landslips are inevitable, the expense of tunnelling may have to be faced. Where even small streams have to be crossed in hilly country, it is well to remember that they may become violent torrents for long enough to cut away their banks and destroy any pillar or support placed in their beds. It is therefore advisable to span the flume clear over these streams, either by a suspension bridge, where the distance is great, or by a reinforced concrete culvert or single arch for short spans.

238. **Sand Traps.**—Where the head on the Pelton wheels is considerable the sand-blast action of solid matter in the water wears away the nozzles, spears, and buckets, and a reasonably clear supply is essential. If there is a large dam and reservoir at the head-works this will be assured, except as regards debris collected *en route* to the power house; if the reservoir is at the power house end of the flume it will indeed collect and deposit most of the solid matter discharged into it, but this will have to be cleared out from time to time at considerable expense. It is on this account expedient to build special sand traps arranged for more or less automatic cleaning. Obviously settling such as is effected for water supply is impracticable; fine mud will take days to settle, and must be left in suspension; but all except the finest silt will be quickly deposited if the velocity of flow is

sufficiently reduced. Considerable expenditure on sand traps or silt tanks may be justifiable, as worn nozzles, spears, and buckets seriously affect the efficiency of the wheels and even cause considerable leakage between the closed spear and the nozzle.

To prevent the flume getting choked, it is preferable to clean the water before its entry, *i.e.* close to the head-works; this, however, is not always practicable, and traps must be placed wherever the ground is favourable. Two identical arrangements of sand traps are seldom found; the problem must be solved according to circumstances, and it will be found interesting. Practically speaking, the flume is both widened and deepened, so as to reduce the velocity of flow to 6 ins. per sec. or less. A strainer or trash-rack may be used for catching floating debris and stones. In order that a sand trap may be self-cleaning, several large gates should be provided, and the floor level should slope fairly steeply from all sides down to each gate. Baffle walls, raised to the level of the flume bottom, will direct the flow of water towards these gates, and the accumulated mud will be dislodged by the rush of water when the gates are opened. The gates must be strong but not too close-fitting, otherwise they will get jammed owing to the mud; they should be opened regularly every day to ensure freedom, even at times when the water is clear. If there is more water available than is required, a small amount can be discharged continuously at these gates, and this will tend to prevent the accumulation of mud on the floor. It is probable that centrifugal action in a suitably designed basin, caused by the radial entry of the water, could be used for the automatic discharge of a good proportion of sand or silt, just as it collects at the orifice of a circular hand basin.

239. Regulating Storage of Water.—A regulating reservoir in a hydro-electro scheme may fulfil two functions; it may serve to augment the quantity of water available at times of heavy load, by storing the unused supply during the hours of light load, and it may act as a reserve against break-down in the water supply between itself and the head-works. Where the supply is plentiful and perennial the first function need not be considered; where the reservoir is of necessity placed at the head-works the second use disappears to a great extent, as a break-down is more likely to occur in the flume than anywhere else.

Consider, by way of example, a hydro-electric scheme with a head of 1 000 ft. and a minimum flow of 15 cusecs. Then about 1 000 kW can be depended upon continuously day and night (§ 201) or 24 000 kWh per diem. If the average load on the station is 500 kW, the daily output will be 12 000 kWh, or half the maximum, *i.e.* the load factor (§ 261) will be 50 %, though the plant installed to meet peak loads would be much greater. Thus we may suppose half of the total output, or 6 000 kWh, to be generated during the three hours of heaviest load, *viz.* 2 000 kW, as would happen in the case of a load mainly for lighting. Then for these three hours the demand would be 30 cusecs and the supply 15 cusecs, so the balance would have to be obtained by storage; 15 cusecs for 3 hrs. = 162 000 cu. ft. In case of break-down to the water supply, this quantity would keep the plant working for $1\frac{1}{2}$ hr. at maximum load, which would not be sufficient unless the risks of break-down were very small; but the amount of storage actually allowed for must necessarily depend on the cost of the reservoir. Where a natural site for a dam exists, it may cost no more to provide a month's full-load supply than to build an artificial tank for one day's supply.

In the example just given the actual output was assumed to be half the maximum possible with 15 cusecs available. Therefore, in the course of 24 hrs., if the efficiency of the turbines remained constant at all loads, half the available water would run to waste, or 648 000 cu. ft. Allowing for the lower efficiency at reduced load, assume that 600 000 cu. ft. would actually run off unused in the absence of storage. This then is the *maximum* amount which could usefully be stored. With this reserve it would be possible to still further increase both the plant capacity (*i.e.* the maximum load) and the total output, assuming that a demand existed. The reserve alone would be capable of giving 5 000 kW for two hours, apart from the 15 cusecs of normal flow still coming in; and the total units of output per diem could be brought up to the maximum possible, viz. 24 000 kWh, on any load factor.

Another example will serve to illustrate how the amount of storage required may be calculated where the dry-weather flow is small and a suitable site exists for a dam across a valley. The data were as follows: Maximum power required at points of utilisation, 224 kW, or 300 E.H.P.; allowing for transmission, 333 E.H.P. from the generators; 370 B.H.P. from the turbines; 493 theoretical water H.P. at 75 % wheel and pipe efficiency. Probable load factor, 30 %; so units delivered to consumers = $224 \times 0{\cdot}3 \times 365 \times 24 = 587\ 000$ kWh per annum (equivalent to 786 000 E.H.P.-hrs.), and units generated, 650 000 per annum. Net available head of water, 220 ft. It was found that the natural flow of the stream would be sufficient to run the plant during eight months of the year, but during four months supplementary storage would be required. With a large reservoir the minimum flow ceases to be important; the average flow determines the necessary capacity. The average flow during these four months was estimated to be $1\frac{1}{2}$ cusecs, which gives 16 million cu. ft. in four months.

From these data, it will be seen that 786 000 E.H.P.-hrs. delivered to consumers is equivalent to $786\ 000 \times 493 / 300$ or 1 290 000 theoretical water H.P.-hrs. in the year; in four months therefore the requirements will be 430 000 water H.P.-hrs. But 1 cusec gives $1 \times 62{\cdot}3 \times 220 / 550 = 25$ water H.P. In one hour this rate of flow uses 3 600 cu. ft. of water and gives 25 water H.P.-hrs., thus using 144 cu. ft. per theoretical H.P.-hr. Therefore the total water used in four months will be $430\ 000 \times 144 = 62$ million cu. ft. Deducting the inflow of 16 million cu. ft., the *minimum* storage required to tide over the dry period is 46 million cu. ft. In most cases storage on this scale for so small a power development would be

prohibitive in cost; had the head been 1 000 or 1 500 ft. the proposition would have been more favourable.

240. **Points in Design of Balancing Reservoirs.**—The construction of dams and reservoirs is beyond the scope of this book, but some practical points may be mentioned. If the turbine pressure pipes take off directly from the reservoir, the effective depth of the latter should be a small fraction of the total head; otherwise the variations of head between full and empty reservoir will affect the working of the plant. Symmetry in design of an artificial tank is of no importance; the object is to get as much storage as possible for a given expenditure, and every foot of ground should be utilised; this applies more particularly to hills, where the levelling off of a bluff is generally necessary to obtain a site. There should invariably be a silt trap immediately preceding an artificial reservoir; otherwise the foreign matter collected by the flume *en route* will be troublesome; a natural reservoir formed by a dam in a stream bed must, of course, take care of itself in this respect, unless it is possible to build a smaller dam farther up-stream for use as a silt trap. An overflow weir, with a safe passage for surplus water, is also essential.

It is sound practice to sectionalise the reservoir where muddy water has to be dealt with, so that one part can be cleaned while another is in use. To facilitate cleaning, there should be a slope of the floor towards the scour outlets. The part of the reservoir from which the pressure pipes are led off should be isolated from the rest, and fed normally with clear water from the top surface, through fine screens and gates; but there must also be valves at the bottom of this chamber for use when the stored water has to be drawn upon. A by-pass from the flume, similarly protected, should be led directly into this draw-off chamber, so that the reservoir can be closed for repairs without shutting down the plant. Obviously this diversion should pass through the reservoir silt trap, or sand will get into the pipes and valves. Continuous gauze screens, revolved by hand or motor, are more satisfactory than fixed screens, which easily get choked. The water-way through these must be sufficient to pass the full draft under the lowest working reservoir depth. If it so happens that the reservoir must be some distance from the power house, it may prove economical not to run pressure pipes for the whole distance; the alternative is to run the pressure pipes up the shortest route

to the reservoir level, and there to put a small open balancing chamber or pen-trough which can be fed from the reservoir by a closed-in horizontal pipe (metal or concrete) which is not subject to any appreciable pressure. If an open channel is used, the head due to the reservoir depth would be sacrificed, and hand regulation of the water would be necessary; this is only practicable where there is a permanent excess of supply over demand.

241. High-fall Projects Depending Mainly on Storage.—A different class of project altogether has been developed in certain areas where the natural conditions were favourable, and especially in the Western Ghat range in Bombay Presidency. Here the monsoon from the Indian Ocean bursts in full force on the crests of the mountains, giving a rainfall of from 150 to over 250 ins. in the course of a few months; for the rest of the year an occasional thunderstorm is the only precipitation. In these circumstances the run-off is extremely high and the streams dry up very rapidly when the rain ceases, so that there is practically no flow for 9 months of the year. In the locality referred to, and possibly elsewhere, there are valleys at a high elevation which lend themselves to storage on an immense scale by means of high dams; but very few such localities have so far come to light. By storing the whole monsoon flow even over a comparatively small catchment, such as is necessarily found high up on a mountain range, an immense volume of water can be stored, sufficient to keep a large power station at work throughout the year, just as large irrigation systems have long been similarly fed.

Thus it will be seen from the data in § 202 that 200 ins. of rain on 20 sq. mls. of catchment will give some 9 000 million cu. ft. of water; this, neglecting losses by evaporation, etc., will on 2 000 ft. head provide

$$\frac{9\,000 \times 2\,000}{500} = 36\,000 \text{ kW-years},$$

which on commercial load factors would enable a plant of from 70 000 to 100 000 kW to be installed. There are existing plants comparable with this example.

242. Types of High-fall Storage Lay-out.—In the utilisation of these high level artificial lakes several methods have been adopted. If there is a direct fall from the lake, or one of a connected series of lakes, to the power house site the conditions are ideal. If the most favourable fall is on the opposite side of the watershed, or if two lakes are so placed, a tunnel is constructed.

Thus, in the Andhra Valley works in India, a dam of 190 ft. forms a lake with a surface area at full supply level of 25 sq. mls. All the water below about 30 ft. from the surface is 'dead,' a lined pressure tunnel being cut through the watershed for about 2 mls. at this point. At the tunnel exit there is a sloping surge pipe, also cut in the solid rock, to counteract the changes of velocity in the tunnel; and from here the pipes are carried down a steep slope to the power station some 1 750 ft. below lake level. The junction of tunnel and pipes carries the stop valves.

In other cases open channels are necessary to carry the water from where it is stored to a forebay from which it is piped down (§ 237).

If in addition to large storage there is also a steady inflow from the catchment area the power possibilities are to that extent increased, as no water need be lost. Thus 1 cusec flowing for a year will give 535 kWh per ft. of head. Storage projects of the nature here dealt with are generally only practicable on fairly high heads, as the cost of the dams per H.P. developed is in inverse proportion to the head.

243. Storage and Flow Combined on High Heads. — The great hydro-electric plants of Norway have the immense advantage of natural storage coupled with perennial flow from snow mountains; the rivers pass through great lakes at high altitude, which before they were used for the purpose had a large water spread. By placing a comparatively low dam at the outlet great storage capacity is obtained, and the draft can be regulated without waste throughout the whole year. Furthermore, in the Rjukam-Notodden chain of power houses there is a lake of this nature between the high-fall plants and the series of low-fall developments already referred to, so that an excess or deficiency of flow from the upper side can be compensated.

Sometimes the combination of two perennial streams, each with artificial storage from a dam, may be possible, as in the Laxapana-Aberdeen project in Ceylon. The advantage of such a site is that each component can be developed separately to its full capacity, if foresight is exercised, without waste of capital on unproductive works. When the power from flow has all been taken up the storages can be developed in turn. In any such case of duplicate or multiple sources the open channels from the

head-works to the forebay can be carried either round or through intervening spurs, according to the ground.

In contradistinction to this development of streams in parallel, there are many instances of power stations in series on a single source. Of these the best known is perhaps the combination of the Vermork and Saakem power houses at Notodden in Norway. The former station utilised part of the head—some 920 ft.—of the great waterfall for the development of 165 000 H.P. for the manufacture of nitrates; and the waters were tailed down to the river below with a considerable sacrifice of the total head of. 600 m. When the war broke out it was decided to use the tail waters in a second station. A tunnel 4 mls. long was therefore excavated along the mountain side, which was too precipitous to carry a surface channel; this tunnel took the tail waters from Vermork to a forebay, also excavated in the solid rock, and thence three tunnels at a very steep angle carry three pipes each down to the second power house, which alone of all the works is on the surface.

244. Storage Lakes.—Wherever a large volume of water is stored for power purposes it has a definite value in H.P.-hrs. or years, depending on the head (§ 202). By means of the mass curve (§ 209) and the draft curve, the conditions can at any time be seen. A complete contoured plan is made of all storage lakes, showing the capacity (in water or in H.P.-hrs.) at all levels ove the offtake. If the locality is one liable to severe droughts to partial failure of the monsoon it may be necessary to carry er a large volume of water for such emergencies; to calculate ne amount so required involves a knowledge of the hydrography of the catchment over a long period, preferably 20-30 years, as well as of the average annual loss by absorption and evaporation. These last may in hot dry climates amount to from 3-10 ft. per annum. The carry-over storage involves heavy additional capital expenditure and therefore merits most careful investigation.

In many cases dams are so arranged that when necessary the water level can be raised by means of temporary flash-boards or permanent collapsing gates; in this way a large extra volume can be impounded at the end of heavy rainfall, or before the close of the rainy season. With low dams the excess water can safely be surplussed over the crest, which acts as a spillway, and gates can

be arranged so as to collapse automatically when topped; a similar arrangement is also often used in river head-works below the entry of a canal. Overhead arrangements can then be made for raising the gates afresh as the flood subsides.

Another useful arrangement is the automatic floating weir. This consists of a long hollow cylinder carried on an axle with a toothed wheel at each end; the wheels engage with teeth on a sloping ramp, so that as the cylinder rises or falls with the water level it moves up or down the ramp. When at the lowest position a projection along the cylinder, parallel to the axis, closes the water-way entirely; the first rise therefore lets more water underneath than a similar rise later on. By means of valves, water can be let into or out of the cylinder, so as to alter its buoyancy as required for regulation. If sufficient excess water comes down the floods top the cylinder as well as flowing under it.

With high dams the surplus water may be discharged by under sluices but cannot be allowed to top the crest; more ordinarily a separate escape is made on a flank or saddle, either over natural rock cut down to the required level or over a masonry weir.

245. **The Forebay.**—Even when the pipes lead off directly from a reservoir, a section of the latter is generally isolated to act as a forebay for protection and control of the pipe inlets; where an open channel is used the forebay also acts as a small balancing tank to meet minor fluctuations of load. The capacity should then be sufficient, if possible, to carry the plant over the period required for water to arrive along the channel. Thus a plant mainly supplying factories may rise from a negligible load up to full load in the course of a few minutes, and may lose its whole load equally suddenly, at the customary hours of opening or closing. It requires nice calculation to open the full supply into the open channel at exactly the right time so that, after traversing the channel for half an hour or more, it arrives just when it is wanted. But, while late arrival means closing down the plant, early arrival means surplussing the whole flow of the channel unless the forebay can carry it.* Often the ground is steep at the forebay, and the requisite capacity is unobtainable; but the value of sufficient storage is great. Occasionally the forebay can be carried along

* For example, a plant with a normal load of 30 000 kW on a head of 1 800 ft. requires 30 000 × 15 / 1 800 or 250 cusecs, equivalent to 450 000 cu. ft. for half an hour.

the contour in the form of a greatly enlarged channel, but this is more expensive to build than a more nearly circular pond. The spill-way may be either at the forebay itself or at the most convenient natural outlet farther up the channel, so long as the levels allow this. Each pipe should have its own intake chamber and screens, shut off from the forebay by gates. Generally automatic arrangements are made by which the gates can be tripped and closed off from the power station in case a break occurs in the pipe line. If automatic valves are used on the pipes themselves an air inlet is used in combination, so that the upper and slighter pipes will not collapse under the vacuum formed.

246. Pipes for High-fall Turbines.—Hitherto it has been assumed that the water has been brought along to a point above the power house, with or without a storage reservoir at some point on the route. From the forebay at the end of the flume or from the reservoir, as the case may be, pressure pipes lead down to the turbines. Various arrangements will be found in different schemes; sometimes a single pipe is used, capable of carrying the full supply, branches being taken off a receiver to the individual machines at the turbine house; preferably each turbine and generator is a self-contained set with its own pipe; or again, several pipes may be put in and interconnected by **T** or **Y** pieces with valves at the power house. Again, the pipe may be of the same internal diameter all the way or may be graduated, the lower sections being of smaller and the upper of larger size than the average required; with high heads this latter method enables pipes of less thickness to be employed where the pressure is greatest. The static pressure on the pipes is that corresponding to a column of water of the same vertical height, whether the actual pipe line be long or short. It is 62·4 lbs. per sq. ft., or 0·433 lb. per sq. in., per ft. of head; therefore for 2 000 ft. head, which is by no means the highest in use, the pressure will be 866 lbs. per sq. in. The pressure is, of course, reduced when water is flowing, on the other hand, it may increase greatly if the flow is suddenly stopped (§§ 248, 251). A detailed mathematical investigation of the forces in high pressure pipe lines and their supports is given by A. Hruschka, *Elek. u. Maschinenbau,* Vol. 40, pp. 533, 546; *Sc. Abstr.*, 305 B, 1923.

247. Size of Pipes; Velocity; Loss of Head.—When calculating the size of pipes, it is well to remember that they will not

remain clean indefinitely; and the loss of head increases greatly as the pipes become encrusted. This loss varies as the square of the velocity, and, as it is important to keep the net head fairly constant, low velocities only are permissible. About 3-4 ft. per sec. may be taken as an average; 7 ft. per sec. should be the maximum velocity in the smallest section of a graduated pipe. The loss of head, H, may be calculated from the following formula: $H = v^2 \times 4m \times L / 2g \times D$,

where v = velocity in ft. per sec.
m = coefficient of friction (*see* Table 36).
L = length of pipe in ft.
g = acceleration of gravity; 32·2 ft. per sec.^{2} at sea-level.
D = diameter of pipe, in ft.

From Table 36 the value of the coefficient m can be found by interpolation on the slide rule near enough for all practical purposes, for such sizes of pipes as will generally be required.

In a particular case the diameter of a turbine pipe was reduced by nearly 3 ins. in a graduated line of 16 ins., 14 ins., and 12 ins. pipe. An incrustation or 'furring up' almost invariably occurs to a greater or less extent; it is as well to provide for it not only by allowing extra diameter, but also with a view to removing the scale after it has formed. This can be done by means of a turbine-type tube cleaner, which is inserted at the top and then driven down the pipe by admitting a limited amount of water behind it. Such a device, however, is unable to negotiate sharp bends (of which there should in any case be none), and must be adjusted where the pipe section alters. It is therefore advisable to provide a chamber of larger diameter than the pipe at all such

TABLE 36.—*Values of m for Flow in Pipes.*

Diam. of Pipe, Ins.	Clean Pipes. $m =$	Slightly Tuberculated Pipes. $m =$	Foul Pipes. $m =$
6	0·006 7	0·007 7	0·011 0
10	0·005 8	0·007 1	0·008 7
14	0·005 5	0·006 6	0·007 9
18	0·005 2	0·006 2	0·007 3
24	0·004 8	0·005 7	0·006 6
30	0·004 5	0·005 3	0·006 0
36	0·004 2	0·004 9	0·005 5

points, with an isolating valve immediately beyond it, and a scour pipe and valve above this main valve. Here the water and the scale will be discharged, and the cleaner adjusted for the next section. In the absence of the isolating valve there is a danger of choking the lower sections and the turbine nozzles.

Tables giving the loss of head at various velocities, for different sized pipes, will be found in catalogues of turbines; they are generally calculated on clean pipes, so an extra allowance of 30 or 40 °/。 will be on the safe side. For small pipes, *see* Chapter 30.

248. Thickness and Weight of Pipes.—Turbine pipes for high falls are made of steel. For exceedingly high pressures they are made direct from the ingot, weldless and perfectly homogeneous; ordinarily either welded pipes, for moderately high heads, or (for medium heads) double-riveted or single-riveted pipes are employed. The thickness of metal (subject to a minimum value of about $\frac{1}{8}$ in., to allow for possible corrosion or damage from falling stones) may be calculated from the formula $t = pr / f$ where t is the thickness, in inches; p the static pressure, in lbs. per sq. in.; r the internal radius of pipe, in inches; and f the working stress in lbs. per sq. in. Of these factors, p is known from the head ($p = 0{\cdot}433\ h$), and r is found from the quantity of water flowing at the determined velocity

$$[r = \sqrt{(\text{cusecs} \times 45{\cdot}8 / v)}, \text{ where } v = \text{velocity in ft. per sec.}]$$

As regards f, the ultimate strength of steel may be taken as about 25-30 tons, per sq. in. and the working stress, f, about 9 800 lbs. for riveted pipes up to 14 000 lbs. for welded pipes. The figures have been arrived at by taking the inefficiency of riveted joints as 0·7 (it should be as high as 0·9) and the factor of safety as 4; in that case

$$f = 25 \times 2\,240 \times 0{\cdot}7 / 4 = 9\,800 \text{ lbs.}$$

or, omitting the rivet factor, 14 000 lbs.

If the design is such that the flow in the pipe cannot be stopped suddenly (as with deflecting nozzles), it is not necessary to allow for shock due to water hammer; but if the flow can be stopped suddenly, this factor must be taken into account, as p in the formula is the *static* pressure. The maximum possible additional pressure in lbs. per sq. in., due to stopping the flow instantaneously, is $63\frac{1}{2}$ times the velocity in ft. per sec.; in practice, it is fairly

safe to assume that not more than double the static pressure will be experienced. In such a case the factor of safety assumed above is halved, and becomes somewhat fine; a lower working stress should therefore be taken.

The weight of plain steel tubes, in lbs. per ft. run, may be taken as $9{\cdot}45t(d + t)$, where t is the thickness of the metal and d the internal diameter, both in inches. For riveted pipes the weight so found should be multiplied by $1\frac{1}{2}$ in small sizes; by 1·4 for a 20-in. pipe; 1·25 for a 40-in. pipe; and 1·15 over 60 ins. diameter.

249. Example of Pipe Line.

By way of example, the following case may be taken. A pipe line was required to serve a 600 kW turbine-driven generator on 1 025 ft. head. The turbine, at normal full load on the generator, would have to give 840 B.H.P., and with an efficiency of 75 °/₀ this involved 1 120 H.P. from the water, requiring 580 cu. ft. per min., or 9·65 cusecs. With an average velocity of 4 ft. per sec. the average area of the pipe would be $9{\cdot}65 / 4 = 2{\cdot}41$ sq. ft., corresponding to 21 ins. diam. In this instance, owing to the high head and considerable quantity of water, it was desirable to sectionalise the pipes; and the nature of the ground divided the whole conveniently into four parts, *viz.* :—

Section (i) Reservoir to pipe=head proper, laid on hydraulic gradient only—Length 650 ft. Head negligible. (Stand-pipe at the junction, *see* § 251.)

Section (ii)	Length 1 140 ft.	Head 420 ft.
Section (iii)	Length 980 ft.	Adding head 60 ft.; total 480 ft.
Section (iv)	Length 1 150 ft.	Adding head 545 ft.; total 1 025 ft.
	Total length 3 920 ft.	Total head, 1 025 ft.

The pipe line decided on was as follows :—

	Diameter. Ins.	Area. Sq. Ft.	Velocity. Ft. per Sec.
Section (i)	24	3·14	3·14
„ (ii)	24	3·14	3·14
„ (iii)	21	2·40	4·1
„ (iv)	18	1·76	5 6

Taking section (ii), the loss of head at full load, when the pipes become slightly foul, will be—

$$H = 3{\cdot}14^2 \times 4 \times 0{\cdot}005\,7 \times 1\,140 / 2 \times 32{\cdot}2 \times 2 \text{ ft.} = 1{\cdot}98 \text{ ft.}$$

Similarly, the losses in the other sections will be (i) 1·14 ft., (iii) 3·5 ft., (iv) 9·4 ft. making a total loss of 16 ft. To this another 4 ft. was added to allow for bends and the obstruction due to rivets, making the total loss 20 ft.

Now these calculations relate to the normal full load of the generators, at

which they are able to work continuously, but all generators are designed to be capable of overload to the extent of at least 25 % for limited periods; therefore the turbines would have to be capable of giving 1 050 B.H.P. at such times. The velocities and losses with the increased quantity of water were therefore similarly worked out to see that they would not be excessive. It will be seen that in these circumstances the maximum velocity in the smallest pipe is 7 ft. per sec.; the total losses also are reasonable, amounting to about 3 % of the total head. Section (i), being under practically no pressure, was specified for mechanical reasons as $\frac{1}{8}$ in. thick. In section (ii) the head is 420 ft., and the maximum static pressure 180 lbs. Therefore the thickness of metal (§ 248) will be $t = 180 \times 12 / 9\,800 = 0{\cdot}22$ ins. or $\frac{7}{32}$ in. In section (iii) the total head is 480 ft.; static pressure, 208 lbs.; $t = 0{\cdot}22$ ins. again, the diameter being reduced. Section (iv) was divided into two equal lengths of 575 ft. of 18-in. pipe. The pressure in the upper half works out to 326 lbs. per sq. in. giving $t = 0{\cdot}3$ in., while in the lower half it comes to 444 lbs., giving $t = 0{\cdot}41$ in.

250. Special Pipes, etc.—In order to determine what pipes are required, the proposed pipe line must be surveyed very carefully, the exact lie and angle of all bends being determined. A small error may add greatly to the difficulties of erection. Where the diameter alters, special tapered pipes are fitted. At convenient points thrust-blocks are required, the pipes being securely anchored to concrete blocks at these places. Expansion pipes may be necessary, but if the line departs from the straight to any considerable extent expansion can generally take place laterally; covering the pipes in and keeping them full of water reduces the expansion almost to zero. Bell-mouth pieces and valves are required at the reservoir or forebay, and both main and scour valves at the lower end. If a receiver is employed, or if pipes are connected by a **Y**-piece, isolating valves are employed. Specials may be either of cast steel or, preferably, built up of riveted plates. On very high heads air-cushions are sometimes fitted at intervals on the line, to reduce the shock when the velocity changes; by fitting two vessels side by side, with suitable cocks, the water pressure can be used to force air into the cushion chamber, or this may be done with a pump. In America the upper sections of long pipe lines, where the pressure is comparatively small, are often made of wood-stave construction, built up on the site to save freight; but this method has not found much favour elsewhere, and is useless where white ants are found.

251. Pipes as an Alternative to Open Channels; Surge Towers.—It sometimes happens that for one reason or another an open channel will not prove satisfactory for bringing the water

to the pipe head, or will prove more expensive than piping for the whole distance. If the use of piping involves a considerable initial length, almost horizontal, some new considerations come in. The first section of the pipe in the example (§ 249) is a case in point. Although 650 ft. long, it was sloping only on the hydraulic gradient, and the normal pressure on it was negligible. If, however, the pipe had been entirely continuous with the lower sections, there would have been possible danger from water hammer. In order to obviate this, and to compensate for sudden changes in the velocity, a vertical stand pipe, open at the top, was placed at the junction of the first and second sections; it was carried to the level of the top of the reservoir, a matter of some 30 ft., and was made of larger diameter than the pressure pipe. As explained in § 232, in the case of a sudden demand, the volume of water stored in the stand pipe would give the main horizontal column of water the chance to come up to speed; in the case of a sudden stoppage, the stored energy of the moving column could force water out of the open top of the stand pipe and thus reduce the shock. Surge towers have been used up to 200 ft. in height, carried on a tower with a small balancing tank on the top. For similar reasons surge pipes are often erected at the foot of descending pipe lines, on the line side of the foot valve. Should the latter be closed quickly in emergency or due to sudden reduction in turbine load, the momentum of the quickly moving water in the descending pipe is expended in forcing water up the surge pipe. Without such a safety device, the valve and pipe would be severely strained or broken. Open surge-towers are obviously impracticable at the foot of very deep descents, but closed ones, with a considerable volume of enclosed air under pressure, are often used (*Proc. Amer. Soc. C.E.*, August, 1917). Automatic relief valves are another alternative.

252. Pipe Joints.—Much ingenuity has been exercised in designing suitable joints for pipes under a high head of water. In the past, plain slip-joints and collar-and-sleeve lead joints have been used for moderate heads; these, however, are not satisfactory except for low heads. A plain flanged joint, with a rubber or copper ring between the faces, makes a satisfactory joint for heads up to 500 ft. or so; such joints have been used on much higher pressures. The flanges, which are riveted on to the pipes, should be pressed out of a steel plate by a die; cast-iron

flanges are unreliable where subject to shocks. Various patent flange joints are also on the market, some of them suitable for very high pressures. Riveting the lengths of pipes together on the site is occasionally resorted to, but it involves high-class labour, and is only suitable for straight runs of large diameter. The best modern joints, such as the 'muff' joint, depend on a wedge action for keeping tight, and these have the advantage also of being to some extent self-adjusting, both as to direction and expansion or contraction. Most turbine makers appear to agree that this is the most satisfactory high-pressure joint.

253. Pelton Wheels and Nozzles.—In one form or another the Pelton wheel is almost invariably used for the development of power from high heads, and no description of this well-known impulse wheel is necessary. The peripheral speed of such a wheel in ft. per sec. is about $0{\cdot}45\sqrt{(2gH)}$; thus on 1 000 ft. head it will be 114 ft. per sec., and the revolutions per minute can be varied according to the diameter chosen for the wheel. The diameter of the water jet nozzle should not be more than one-fifteenth that of the wheel to get the highest efficiency; if a greater volume of water is required, more than one jet is used. Assuming that in any particular case the working head, H, and the required B.H.P. of the turbine are known, and consequently the quantity of water also, the size of the nozzle may be determined by the formula—

$$d = \sqrt{(1{\cdot}28Q / v)},$$

where d = diam. of nozzle, in inches.

Q = discharge at the nozzle, in cusecs.

v = velocity of issuing jet (§ 214 = $0{\cdot}97\sqrt{(2gH)}$).

If two or four nozzles have to be used, the discharge, Q, will be halved or quartered in working out their diameter.

Thus if a 340 B.H.P. turbine is required to work on 1 000 ft. net head, the quantity of water required, Q, will be 4 cusecs, assuming 75 % efficiency (§ 201).

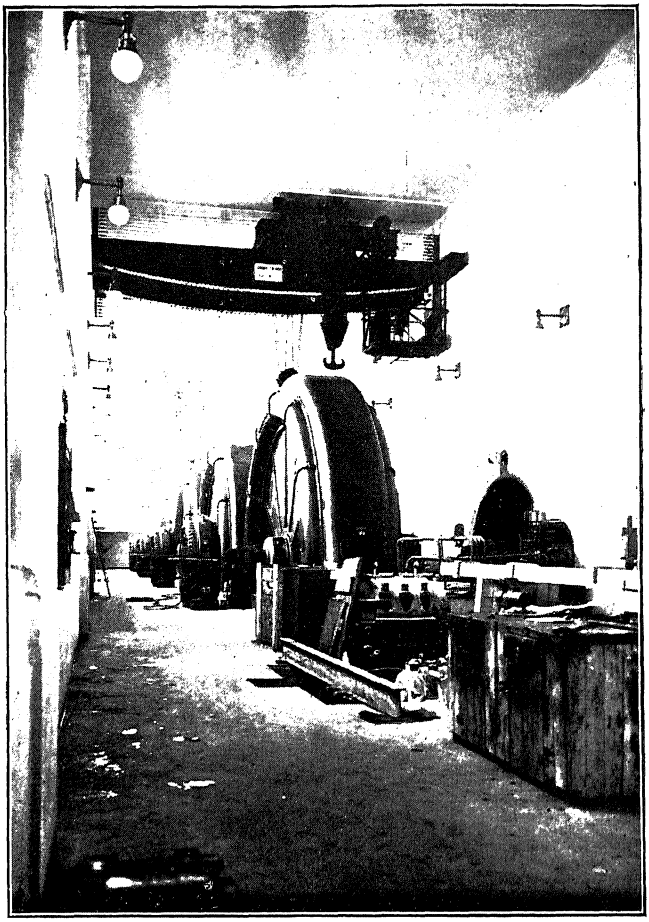
The constant $v = 0{\cdot}97\sqrt{(64 \times 1\,000)} = 245$,

hence $$d = \sqrt{(1{\cdot}28 \times 4 / 245)} = \sqrt{0{\cdot}021} = 0{\cdot}145 \text{ ft. or } 1{\cdot}73 \text{ in.}$$

Now the peripheral speed of the wheel is $0{\cdot}45v$, or 110 ft. per sec. If the diameter of the wheel is 15 times that of the jet, or 2·16 ft., the speed will be

$$n = 0{\cdot}45v \times 60 / \pi \times D = 110 \times 60 / 3{\cdot}14 \times 2{\cdot}16 = 970 \text{ r.p.m.}$$

Each wheel must be capable of being isolated from its supply pipe by a valve, apart from the regulating mechanism, and the

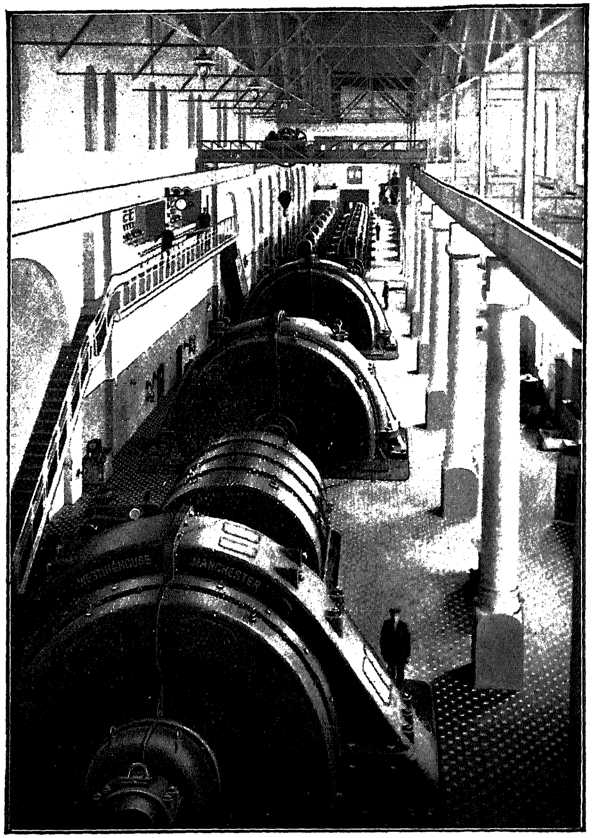


Metropolitan-Vickers Electrical Co., Ltd.

VIEW ON THE GENERATOR FLOOR OF THE RAANAASFOSS POWER HOUSE.

Six horizontal double Francis type runners are placed in an open pit and coupled to six generators, each of 12 000 kVA, 7 500 V, 3-phase, 50 cycles, 107 r.p.m., enclosed type, self-ventilated, with direct coupled exciters. Energy is transmitted to the substations at 50 000 V and 17 000 V.

[To face p. 352.



Metropolitan-Vickers Electrical Co., Ltd.

INTERIOR OF THE TYSSEFALDENE HIGH-FALL POWER HOUSE.

Seven 4 100 kVA, five 12 000 kVA, and two 14 000 kVA generators are driven by Pelton wheels. The 12 000 kVA sets in the foreground run at 250 r.p.m. and generate current at 12 500 V, 3-phase, 25 cycles. The outside diameter of the machines is 19½ ft. and the stator bore 12½ ft. Cooling air is led into the machines through shafts in the basement, and is exhausted into a duct leading to the fjord.

[*To face p.* 353.

closing of the ordinary type of balanced gate valve requires considerable power where the head is great; slow closing, however, is necessary, to prevent water hammer. Where more rapid closing is admissible the Johnson balanced cylindrical valve is often used. This consists of a spear attached to a plunger, working in a cylinder concentrically placed in the pipe, which normally allows a full annular water-way; but when forced forward the spear closes the outlet passage. The plunger is actuated differentially, by admitting or discharging water under the normal pipe pressure or atmospheric pressure, as the case may be, by means of an external cock.

254. **Speed of Wheels for Driving Alternators.**—By increasing the wheel diameter the speed can be reduced; the actual speed (and consequent size of wheel) is generally determined by that of the generator to be driven, unless the drive is indirect, as with belts. In most cases a turbine is required for driving an alternator; assuming that the British standard frequency of 50 cycles per sec. (§ 12) is used, *i.e.* 3 000 cycles per min., the r.p.m. (3 000 / No. of pairs of poles). This gives speeds of 250, 300, 333, 375, 428, 500, 600, 750, and 1 000 r.p.m., corresponding to various numbers of pairs of poles, and the turbine must be of such size as to run at one or other of these speeds.

255. **Regulation of Impulse Wheels.**—The power given out by a wheel at its correct speed may be diminished either—

(*a*) by diverting the whole jet from its true point of impact on the buckets, or

(*b*) by deflecting part of the jet off the buckets altogether, or

(*c*) by reducing the size of the jet.

Where a diverting nozzle is used the reducing pipe and nozzle are hinged, so that the whole can be moved up or down either by a hand-wheel or an automatic governor. The full discharge goes on, whether the power generated be great or small, so it is only where a large excess of water is available that the method should be used. The same result is obtained by using a deflector, which moves concentrically with the wheel and cuts into the jet from above; this method is equally rapid in action, but is only employed in combination with the needle valve presently described. By reducing the size of the jet the efficiency can be kept sensibly constant at ordinary loads, and the most can be made of a small quantity of water. If a wheel is put in which it is known will

not be working at above half its full load for the first year or so, then a nozzle can be temporarily fitted to give this half load; later on it can be changed for a full-sized nozzle. This is often done, but it leaves the question of regulation down to no load (*i.e.* light running) untouched.

In order to keep an impulse turbine wheel running at constant speed under varying loads, it is customary to use a circular nozzle with a tapered spear or needle centred in it; by advancing or retracting the needle, it reduces the area of the jet without breaking it up, and so regulates the power. The adjustment of the needle can be effected by hand; if the governor acts either by deflecting part of the jet or by diverting the nozzle, the attendant can then manipulate the needle valve, and thus save water, and, as the effective area of the nozzle is decreased by the spear, the governor will bring back the jet to its normal action. Of course, if a sudden heavy demand for additional power arises, it cannot be met until the needle has been opened up, and this is not a very rapid process. The best possible arrangement is an automatic combination of needle and deflector or diverter, the whole worked by the governor; rapid alterations in the power demand are met by the deflector or diverter, and the needle then more slowly adjusts its position to give the maximum efficiency under the new conditions. An ingenious method of effecting this is described in *Engineering Record*, August 16, 1913.

The methods already described keep the jet cylindrical but either reduce its size or deflect it from the buckets. In the Seewer system of automatic governing for high-pressure Pelton wheels, which also embraces the two elements of speed regulation and pressure regulation in the pipe system, the jet is made to diverge instantaneously in the form of a cone, more or less according to the reduction in power required; while the usual concentric needle is used, in conjunction with the system, for the more gradual closing down of the jet to a reduced diameter and a return to cylindrical form. The needle is cylindrical up to a short distance from its point and flat diverter plates are mounted between the needle guide and the nozzle. Normally, these plates act as meridional guides and preserve the cylindrical form of the jet; but by inclining them simultaneously through the same angle a rotating component is introduced into the water flow and the jet diverges. The maximum divergence is about 60° when the plates

are turned through 22°. Part of the jet then misses the buckets, while part strikes the back of them; the needle meanwhile closes and the plates return to their normal position. On load increases the needle alone acts. The diverter plates are pivoted on spindles carried into the centre of the hollow needle and are thence connected to the servo-motor actuated by the governor. The power required from the servo-motor is much less than with other types of governing and also varies less with the size of the wheel as, instead of acting at the point of maximum jet velocity, the vanes are working in the comparatively low velocity of the admission pipe round the needle.

256. Turbine Governors.—Many types of governors are made for regulating turbines and impulse wheels. They range from simple mechanical governors, with indifferent regulation, up to the most exact hydraulic governors for use in hydro-electric plants. To actuate a hydraulic valve requires far more power than the corresponding process with a steam engine governor; and this is true also with a spear or deflecting nozzle or a combination of the two. Consequently a hydraulic relay is generally employed; the centrifugal governor actuates a light relay, which in turn operates on the valves of a powerful hydraulic cylinder, the movements of which work the regulating gear. Generally oil under pressure is used in the cylinders, involving the use of a subsidiary oil pump; this obviates all danger from dirt and grit. In other cases either the whole or a part of the working head of water is utilised, in which case a subsidiary governor pipe is preferably employed; the quantity of water used is of course very small, but it must be entirely free from foreign matter, and two parallel filters must be used to enable each to be cleaned in turn. Notwithstanding the makers' claims, the governor is generally the most troublesome part of a turbine plant and the most difficult to keep in accurate adjustment; a large plant has on occasion been completely wrecked through a governor sticking; it is, therefore, economical in the end to buy the best that can be obtained. It is usual to specify the foot-lbs. (from 2 000 to 100 000) which the cylinder can deal with. In the best governors about $\frac{1}{2}$ sec. elapses between the occurrence of a change of load and the commencement of the movement of the turbine gate or spear; the time taken to close the fully open gate, etc., when the whole load is thrown off, varies from 2 secs. upwards. These

intervals are sufficient to enable the speed to vary somewhat, although the provision of a properly designed flywheel keeps the variation down. If 25 % of the load is thrown off suddenly, the change of speed will be from 3-5 %; if full load is thrown off, the momentary change of speed may be from 10-15 %, but the normal value is soon restored. In the case of a gate or needle valve closing rapidly, there may be a considerable rise of pressure in the pipe line, due to water hammer; if the line is a long one, special relief valves may be used, but these are less certain in action than surge pipes (§ 251), though cheaper in first cost. The best types of relief valve work in conjunction with the governor, and are thus positive in action.

There is one plant in India which is worked entirely without governors, *viz.* that at Darjeeling. The governors originally supplied were actuated from the pressure pipes without the interposition of filters, and consequently they never worked well. After the whole plant had been overwhelmed by a flood and landslide in 1897, the governors were removed; and from that year up to the present time a coolie has been stationed at each turbine to regulate it by hand according to the tachometer. A subsequent extension was controlled by an oil-pressure governor for some time, but this also failed occasionally and took to 'hunting,' with the result that hand regulation was adopted exclusively. The work is purely mechanical and can be entrusted to a man with no knowledge, but the method is only suitable for small installations and where cheap native labour is available.

257. The Tail Race.—Impulse wheels discharge their water directly into the tail race; there is, of course, no draft tube. The tail race must be of ample size to give a free exit to the water, and it should have a deep water cushion to take the actual discharge, owing to the high residual velocity under large heads. Under very high pressures a water cushion alone is insufficient to protect the masonry or concrete. A cast-iron block or a baulk of timber may be used as an additional buffer, or the water may be made to impinge on a steel plate bent to a suitable transition curve, so as finally to discharge the water horizontally in a long water cushion. The tail race should be so designed that when the jet is deflected off the buckets it has an unobstructed passage to the outside air through the tail race passage.

258. Bibliography (*see* explanatory note, § 58).

STANDARDISATION.

I.E.C. Publication 29. Prime Movers for Electrical Plant: Nomenclature of Hydraulic Turbines.

BOOKS AND REPORTS.

Natural Sources of Energy. A. H. Gibson (Cambridge Univ. Press).

Report of the Water-Power Resources Committee (H.M. Stationery Office).

Water-Power in the British Empire. Sir Dugald Clerk and A. H. Gibson (Constable).
Triennial Report of the Hydro-Electric Survey of India. J. W. Meares (Constable).
Water-Powers of British Columbia. A. V. White and C. J. Vick (Commission of Conservation, Canada).
Hydro-Electric Development. J. W. Meares (Pitman).
Tidal Power. A. M. A. Struben (Pitman).
Hydro-Electric Power Stations. D. B. Rushmore and E. A. Lof (Wiley).
Hydraulic Power and Hydraulic Machinery. H. Robinson (Griffin).
Hydraulic Machinery. R. G. Blaine (Spon).
Hydraulic Turbines. R. L. Daugherty (McGraw-Hill).
Water-Power Engineering. F. F. Fergusson (Pitman).
Also, many useful publications of the Dominions Water-Power Board and the Hydro-Electric Commission of Ontario. Most countries have now water-power surveys in being or under consideration; particulars of the latest official publications can be obtained from the consular representatives of the countries concerned.

Papers.

Development and Storage of Water for Electrical Purposes. J. W. Meares. *Jour. I.E.E.*, Vol. 57, p. 426.
Hydro-Electric Resources of the Scottish Highlands. M. Maclean. *Jour. I.E.E.*, Vol. 60, p. 902.
Notes on Water-Power Development. A. H. Gibson. Presidential Address British Association, 1921.

CHAPTER 11.

MAXIMUM DEMAND, LOAD FACTOR, AND DIVERSITY FACTOR.

259. Maximum Demand.—Where an electrical installation draws its supply of power from the mains of a public company there is always power available for every lamp or other consuming device therein, although, as explained in connection with tariffs (§ 269), the cost of the supply per unit may vary according to the proportion of the apparatus in the whole installation in use at one and the same time; where, on the other hand, the supply is obtained from private plant, the engines and dynamos must be large enough to meet all demands on them, unless accumulators are also installed. The initial cost of the plant depends on its size and the duty it is called on to perform. It is seldom necessary to install plant capable of supplying power to every lamp, etc., at one and the same time, and in order clearly to explain the principles on which the size of plant must be based certain technical terms must be introduced, defined, and explained, *viz.* 'maximum demand,' 'load factor,' and 'diversity factor.' The maximum demand is really self-explanatory, representing in any particular case the actual maximum number of watts or kilowatts required for a specific purpose. Thus one particular person's maximum demand may be equal to the combined power required by all the apparatus he has installed, *e.g.* a small workshop with a single motor and nothing else. Another person's maximum demand may be only three-quarters or one-half of what would be needed by all his apparatus, owing to the use of the different items not being coincident in time. The maximum demand on a feeder or any line supplying a number of different persons is, therefore, the sum of all the actual *simultaneous* demands (not necessarily or even generally their maxima) from the individuals, at the time when *this sum* reaches its highest point. The maximum demand on a power house is, in the same way, the sum of the simultaneous

demands on all the outgoing feeders or lines, at the time when this reaches its highest point.

260. Maximum Demand: Analogy from Water-supply and Steam.— Where electric supply is in question a clear comprehension of the meaning of the term 'maximum demand' is essential, and this may best be obtained by considering analogous conditions in other branches of engineering. The simplest illustration may perhaps be taken from water-supply. In the roads are large water mains, and in a house are pipes and taps capable in the aggregate of discharging a certain quantity of water in gallons per minute; if there were a clear passage from the mains to the house an unrestricted supply, and perhaps great waste, would result; and in order to prevent this all the water from the mains has to pass through a small ferrule. Leaving out of consideration the regulating tanks in the house, which modify the conditions in practice, it is evident that if all the taps are left open the ferrule will limit the maximum rate at which the supply can be drawn off to a given number of gallons per minute; in other words, the ferrule is designed to limit the 'maximum demand' to what is deemed necessary for the house. The occupier may draw off water at this maximum rate for the whole 24 hrs. or for 1 hr. only, or he may never require to use the full capacity of his ferrule at all; but he can never draw off from the mains at a rate in excess of what the ferrule allows.

A somewhat more complicated, but perhaps closer, analogy may be taken from steam supply. Suppose a number of small industries to be concentrated at a certain spot, each having a small boiler and engine, some working all the 24 hours, some during the day only, and some during the night only. A member of the community offers to put up a large central battery of boilers and to distribute steam to the colony, thus saving the labour and waste involved in a number of inefficient units. The profit to be obtained from this venture will depend on the total amount of steam sold at a remunerative rate, and in fixing this rate the owner will have two factors to consider, *viz.*:—

(*a*) Capital charges, which are independent of the amount of steam generated and sold, but which depend on the total steaming capacity or horse-power of the boilers installed; and

(*b*) Charges for fuel, etc., varying to a great extent with the total amount of steam generated.

We have here then two distinct factors, *viz.*:—

(i) The *maximum horse-power* which the boilers are capable of supplying; and

(ii) The *total horse-power-hours* which they do in fact supply.

Before laying down his plant the supplier of steam will want to know the requirements of each customer; not only the total amount of steam that customer will want during the day, but also the *maximum rate* at which he will require steam *at any one time*, *i.e.* his maximum demand. This will be proportional to the *maximum horse-power* in use at any time, which will generally be much in excess of the average. This maximum demand is independent of time; it may last for half an hour or five hours. Having thus ascertained the maximum demand of each consumer, and the hours when he will probably be using this maximum, the supplier will be in a position to calculate the sum of all the maximum demands at all the different hours, and thus to ascertain the maximum rate at which he will ever have to generate steam; this will determine the number and size of the boilers and the prime cost of, and capital charges on, the central boiler installation.

It is quite clear from the above that the rational method of charging a consumer for the steam supply would be at a certain rate per pound, covering the fuel and other working costs, *plus* an amount covering the capital charges for which the particular consumer had been responsible by his maximum demand, *i.e.* by his method of demanding supply. The former rate of charge would be the same for all consumers, the latter would not, but would be heavier in proportion for those who demanded steam at the greater rate. This is precisely the basis of the maximum demand tariff for electricity supply, to which reference is again made in §§ 264, 272, 275, *et seq.*

261. Load Factor.—In technical phraseology the load factor is the ratio between the actual output of a power station in units and the output that would result if the average demand was equal to the maximum. Put in the form of an equation it is—
Load Factor =

$$\frac{\text{Number of units sold} \times 100}{\text{Max. simultaneous load on feeders in kW} \times \text{Hours of supply period}} = x\ \%.$$

For example, a plant has been laid down consisting of three sets each of 100 kW, of which one is kept in reserve. The working sets can then give 200 kW, and it may be assumed that the maximum load on them reaches this figure at some time during the year. Now if the average demand were equal to the maximum, the load would be 200 kW throughout the year, and the total output of the plant would be 24 × 200 × 365 = say $1\frac{3}{4}$ million units (kWh). If the actual output is 1 million units per annum the annual load factor is 57 %, and so forth.

Sometimes it is more convenient or more logical to deal with the daily, weekly, or monthly load factor. The only difference is in the period over which the actual output is reckoned and during which the maximum demand is observed, but the monthly load factor is generally different from the annual load factor and from that reckoned on a 24-hr. basis.

The load factor of an individual is similarly calculated from—

$$\text{Consumer's load factor } (\%) = \frac{\text{Units consumed} \times 100}{\text{Maximum demand} \times \text{Hours of supply period}}.$$

Except in the case of supply from a plant that is only working for part of each day, the hours of supply are always reckoned as 24 per diem or 8 760 per annum. The importance of good individual load factors, *i.e.* such as approach as near as may be to 100 %, will be appreciated as we proceed. Of all work using electrical energy the various electro-chemical industries have the best individual load factors; such factories may work for 24 hrs. a day throughout the year. This is also sometimes true of pumping plants, especially in mines, but here the power required will be a comparatively small proportion of the total power used for

all purposes. Street lighting averaging about 11 hrs. per diem has an annual load factor of $\frac{11 \times 100}{24} = 46\ \%$. Private lighting has the worst load factor of all, often not more than 5-8 %.

262. Diversity Factor.—The term 'diversity factor' is unfortunately defined in several different ways, and although the expert can generally tell what is meant this leads to confusion. It is sometimes stated that diversity factor = ratio of actual maximum load on feeders to the sum of the maximum demands of all consumers, or, in the form of an equation—

$$\text{Diversity factor} = \frac{\text{Max. load on feeders in kW} \times 100}{\text{Sum of consumers' maximum demands in kW}} = d\ \%.$$

Thus, if the maximum load on the feeders is 100 kW and the sum of the individual loads is 200 kW, the diversity factor is 100 × 100 / 200 = 50 %.

On the other hand, the International Electrotechnical Commission in 1908 defined diversity factor as 'the number obtained by dividing the sum of the maximum loads of the individual consumers supplied by any works during a given period of time by the maximum load delivered from the works during the same period.' This gives a number instead of a percentage, *i.e.*

$$\text{Diversity factor} = \frac{\text{Sum of consumers' maximum demands in kW}}{\text{Maximum load on feeders in kW}}.$$

In the example given above this would be 200 / 100 = 2.

A leading article in *The Electrician* (Vol. 72, p. 372) supports this latter and more authoritative definition, and it is to be hoped that uniformity will presently be reached. On the first basis a better diversity factor involves a lower percentage, which is contradictory and confusing; on the I.E.C. basis a better factor is also represented by a large number, as it naturally should be. The same results will of course be obtained if the loads are stated in H.P. or in amperes at the declared pressure of supply. The 'given period of time' may be a day or a month or a year, according to the circumstances, and the diversity factor may be that on one feeder, or other line, or on a whole works. C. W. Charlesworth (*El. Rev.*, Vol. 89, p. 161) gives the following values for the diversity factor of various loads: lighting 1·1-1·5, average 1·25; power 1·5-3·0, average 2·0; heating and cooking 4-10, average 7·0. Examples follow later (§ 264).

263. Diversity Factor and Load Factor; Analogy from Steam.—Pursuing the example of § 260, it will be seen that if the maximum demands of all the consumers happen to be required at the same time the plant must be capable of supplying the sum of them all, and the capital cost will be very high. On the other hand, it will often so happen that the hours at which the different consumers are using their maximum demands differ greatly; in this case the capacity of the boiler need only be such as to meet the *highest sum of maximum demands at any one time*, and the installation is said to have a good 'diversity factor.' Obviously with a good diversity factor the capital charges are reduced and lower inclusive rates can be charged.

If one of the consumers, in the case we are considering, required steam at a steady rate throughout the whole 24 hrs., so that his maximum demand were equal to his average demand, he could evidently be supplied profitably at a lower rate of charge per lb. of steam than another consumer with the same maximum demand and a very low average demand. The former would have a good 'load factor,' *viz.* 100 °/₀, and the latter a bad one, perhaps 10 °/₀. In the case of the central boiler plant, if in the course of working the conditions were such that all the boilers were working near their full power all the time the plant would be said to have a good 'load factor,' and the working costs would be low. Both these two varieties, *viz.* consumer's load factor and plant load factor, are met with in electric supply. The most favourable conditions for cheap supply will obviously be those where the size and cost of the plant is low, owing to a good diversity factor, and the daily output of each unit of plant is large, owing to a good load factor. As shown by the example in Fig. 50, § 266, a high diversity factor is impossible if individual load factors are very high, but this does not matter because the large plant required (owing to the low diversity factor) is highly productive (owing to the high load factor).

264. Maximum Demand, Diversity Factor, and Load Factor in Electric Supply.—If the explanations in the preceding paragraphs have been followed, it will be evident that they can be translated into electrical terms. Horse-power and electrical power in kilowatts are convertible terms, both representing the *rate* at which power is being used: so also are horse-power hours and kilowatt hours or units, both representing the *amount* of power used: and yet the confusion of watt and watt-hours is a constant source of difficulty. Substituting motors or other current-consuming apparatus for the independent engines, and an electric power station for the boiler plant in the above illustration, the conditions remain precisely as stated. If the maximum demands of the various motors or other apparatus (expressed in kilowatts) occur at all hours of the day and night, the diversity factor of the power station will be good, and the plant will be comparatively small (and inexpensive) in proportion to what it would be if the contrary were the case. If, in addition, the demand for power throughout the working hours is fairly constant, the plant will

have a good load factor, and will be earning a good return on its cost all the time. The consumers' maximum demands and the times at which they occur will always therefore be of importance.

The ideal case of a station supplying a number of loads each of which is constant during the 24 hrs. is unattainable in practice. The actual total load on the station varies from hour to hour and is represented by a more or less irregular curve (*see* Figs. 49-51, §§ 265, 266). Addition of a constant 24-hr. load to the existing load curve will improve the load factor of the station, but a yet greater improvement therein would be effected by adding the same additional output during off-peak hours so as to increase the total output without increasing the maximum load. In other words, whilst the percentage value of the peaks in a load curve can be reduced by adding constant loads to the latter, better results can be obtained by adding loads which will fill up the hollows of the curve.

From the supplier's point of view electric lighting (other than in streets) is by no means a satisfactory 'load,' owing to the limited hours of use. Plant lying idle is costing as much in capital charges, for interest and depreciation, as when it is fully loaded. Consequently, by the bait of a low tariff for other purposes, undertakers seek to encourage the use of electrical energy in more profitable directions, to the advantage both of the supplier and consumer. In the domestic field, these applications of electricity include electric fans and motors, heating air or water, cooking and minor domestic apparatus. These have a far better diversity factor than lights.

265. Some Practical Examples.—In very small lighting installations the maximum demand may amount to 80 or 100 °/ₒ of the wattage of lamps installed; and, on the other hand, it may amount only to 33 °/ₒ or so of the wattage installed in a large installation. In assessing primary charges under the pre-war 'telephone' lighting-tariff (§§ 272, 273) at Marylebone (London), the maximum demand assumed was 70 °/ₒ of the wattage installed for lighting, *excluding* convenience lights (*i.e.* lamps in cupboards, cellars, pantries, and so on). Probably it is not far wrong to assume 66 °/ₒ maximum demand on the first 10 lamps in a domestic lighting installation and 33 °/ₒ thereafter, or, say, 50 °/ₒ of the total lighting wattage installed in an average middle-class home. According to Mr. Seabrook (*Journ. I.E.E.*, 48, p. 394),

it has been found in Chicago that the average residence percentage of maximum demand to watts installed is—

90 %	in a	300 W	installation.
64 ,,	,,	500 W	,,
48 ,,	,,	1 000 W	,,
46 ,,	,,	2 000 W	,,

In churches, theatres, shops, and offices, the whole of the lights may be in use at once, and the maximum demand consequently equal to the maximum possible. Where motors are used for pumping or other domestic uses, the work can generally be done during daylight hours, when the lights are off, and the M.D. will not be affected—unless, of course, the power taken by the motor is greater than that taken by the lamps, in which case the former determines the M.D. Where electric heating and cooking are used the lighting and power loads inevitably overlap, and the M.D. is raised. In such cases the power load will generally be much greater than the lighting load, and the M.D. must be worked out according to the apparatus installed and the probable hours during which both light and power will be in use together. The domestic M.D. for lighting supply is generally about 8 P.M., but if electric cooking be practised the maximum evening demand is shifted to 6 or 7 P.M., according to the hour of dining, and it is often found that the actual maximum demand occurs just before breakfast in winter, when a quantity of heating and cooking apparatus is in use in addition to a certain amount of lighting. In India the domestic M.D. generally occurs at about 8 P.M., whether the load is lighting only or mixed lighting and power. Reference may be made to the examples in § 275 and Chapter 25.

It will be instructive here to give a working example going beyond the bounds of a private installation; say, for a small town in the tropics. The conditions assumed are set out alongside Fig. 49 which shows the 'load curve' (kilowatts plotted against time) for each of the component loads, and also the total load imposed upon the station by the sum of the individual loads.

Load (i) will be represented by a straight line at 50 kW from about 6 P.M. to 6 A.M.; its individual load factor is 50 %. Load (ii) will be represented by a straight line at 40 kW throughout the 24 hrs.; its load factor will be 100 %. The curve representing load (iii) has been drawn of the approximate shape it would be in practice, the load beginning at about 4 P.M., rising rapidly to a maximum

at 8 P.M., and thereafter dropping down to a very small night load, the whole curve corresponding to the consumption assumed; its load factor is only 13 %. Load (iv) yields a much more uniform curve than the previous one; it will be lowest in the early morning, will be at its maximum in the early afternoon, will drop somewhat during the hours when people are out of doors, will rise again about the dinner-hour, and will then drop to the steady all-night load; its load factor during the six-month working season to which the curve relates will be 40 %, whereas it will be practically zero during the rest of the year. Load (v), the commercial motor load, will come on in the early morning, will probably drop somewhat at midday, and will, for the most part, stop about 6 or 7 P.M.; its load factor will be 35 %. By adding the ordinates of all the curves hour by hour the total load curve (vi) is obtained, showing a maximum load *on the plant* of 650 kW. As

(i) *Public Lighting.*—50 kW steady load for an average of 12 hrs. a night throughout the year—6 P.M. to 6 A.M.
(ii) *Pumping.*—40 kW steady load throughout the 24 hrs. all the year round.
(iii) *Private Lighting.*—550 kW of lights installed; maximum demand 350 kW between 8 and 9 P.M. Consumption equal to 2 hrs.' use of all lamps daily throughout the year. Practically no all-night load. Maximum load variable.
(iv) *Fans.*—350 kW of fans installed; maximum demand 250 kW between 1 P.M. and 4 P.M. A good all-day load and a fair all-night load for 6 months in the year.
(v) *Motors.*—400 kW installed; maximum load 180 kW between 9 A.M. and noon; a good load all day and practically no night load.

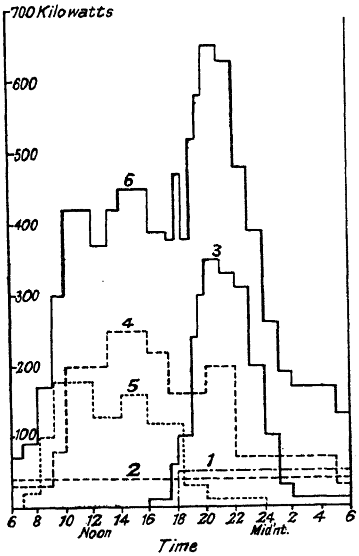


FIG. 49.—Load curves for a small town.

the values assumed are maxima, the average values will be considerably lower, especially during the season when fans are not running. The daily load curve, of which Fig. 49 is an example, varies of course from day to day. Many engineers have their daily load curves drawn out on cardboard and then cut out and stacked vertically in a box, like a card index catalogue; the resulting mass of cards, when compressed close, gives a solid graphical representation of the conditions obtaining over any period.

From the curves in Fig. 49 much information can be extracted. In the first place, the area of each to the base line is a measure of the units consumed. In the figure as reproduced, the horizontal scale is 0·075 in. to 1 hr. and the vertical scale is 0·075 in. to 20 kW, so that each 0·075 in. square (*i.e.* 0·005 64 sq. in.) corresponds to 20 kWh; in practice larger and more convenient scales are used. The ratio of the area under each curve to the total area of the rectangle in which

it is contained is the load factor of that particular curve, giving the results enumerated above. The peak of the aggregate curve shows the number of kilowatts the plant must be capable of giving, and the ratio of the area of that curve to its rectangle gives the load factor of the plant on the particular day for which it is drawn. If similar curves are made for average summer and winter conditions, the annual consumption and load factor can be found from the various areas. Table 37 gives the probable results under the conditions set forth.

TABLE 37.—*Illustrating Conditions of Supply.*

Nature of Load.	Kilowatts Connected.	Max. Demand. kW.	Average Demand and Hours of Use.	Units per Annum. kWh.
(i) Public lights . .	50	50	50 kW for 12 hours for 365 days	219 000
(ii) Pumping . .	40	40	40 kW for 24 hours for 365 days	350 000
(iii) Private lights . .	550	350	2 hours' use all lights per day	400 000
(iv) Fans . . .	350	250	100 kW for 24 hours for 180 days	430 000
(v) Motors . . .	400	180	125 kW for 12 hours for 365 days	532 000
Total . .	1 390	870	—	1 931 000

It will be observed that the total in the M.D. column is 870 kW, whereas in Fig. 49 it is only 650 kW; this is due to the fact that in practice the various maximum demands are not simultaneous, or, in other words, *to the diversity factor of the various loads.* For that matter they would not even occur on the same day, except by coincidence. With the assumed steady street lighting and pumping the load factor over the whole year will be an exceptionally good one, *viz.* 1 931 000 × 100 / 650 × 365 × 24 = 34 %; it will be higher than this on the curve, but there all the maximum loads are assumed to occur at different times on the same day, which would hardly be likely to happen. Actual computation shows that the total load curve in Fig. 49 has an area of 11·3 sq. ins., while the containing rectangle is 21·7 sq. ins. The ratio between these shows a daily load factor for this one day of 52 % or 8 160 units generated in one day against a possible 15 600. The total units *per annum* shown in Table 37 are less by about 36 %, *viz.* 1·9 million against 3 million.

The diversity factor for this particular day will be 870 / 650 = 1·34 or, if expressed by the first method explained in § 262 as a percentage, 0·75 %. This too will vary from day to day.

Reference to Fig. 49 shows that the plant is only fully loaded from about 6-10 P.M. It would pay to take additional load at a very low rate if these hours were excluded by agreement. In the U.S.A. a large business has been worked up in charging batteries for electric automobiles (Chapter 36) during the hours

of light load. It is said that 65 million units per annum are used for this purpose.

Elsewhere arrangements are made so that pumping loads, or water heating, are carried out at all hours of the day *except just at the peak load;* in this way they may add greatly to the number of units usefully sold without causing any addition to be made to the size of the generating plant. Furthermore, the actual cost of these units to the supplier is merely the extra cost of fuel required to produce them, and therefore far below the total average cost of all the units sold, so that such off-peak supply is doubly profitable.

266. Industrial Load Curves.—Fig. 50 shows a load curve such as will be more or less typical of a water-power plant supplying electro-chemical or metallurgical industries.

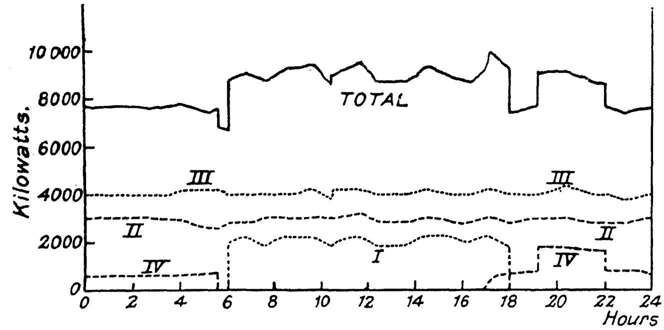


FIG. 50.—Load curve typical of electro-chemical or metallurgical industries.

In this are shown four separate load curves and their summation.

No. 1 takes about 2 000 kW from 6 A.M. to 6 P.M.

Nos. 2 and 3 take about 3 000 and 4 000 kW respectively throughout the 24 hrs. on some continuous process.

No. 4 represents the local load of the town and of the continuous factories in lighting and other subsidiaries, rising to a maximum of 1 800 kW.

Here the load factor of the whole supply is about 86 %—even this is sometimes exceeded in such works—and the diversity factor of the 4 separate loads is 11 700 / 10 000 or 1·17. The individual load factors are so high that there is not much room for diversity.

The curve in Fig. 51 is an ideal one, with a diversity factor and load factor such as the station engineer seldom realises except in his dreams; but nevertheless it represents an ideal towards the attainment of which he can do a great deal. Only the peaks of the several loads are shown, and the summation curve is therefore only approximate. Inspection, however, shows the combined peak load to be about 1 640 kW at the time when all the various lighting loads overlap with cooking at 8 P.M., or perhaps 7 P.M. in actual fact. The individual peaks are—

Street lighting	300
Cooking	400
Industrial power	740
Private lighting, etc.	1 000
Sewage pumping	500
Total	2 940

The diversity factor is therefore 2 940 / 1 640 or 1·8 combined with a load factor of nearly 75 %.

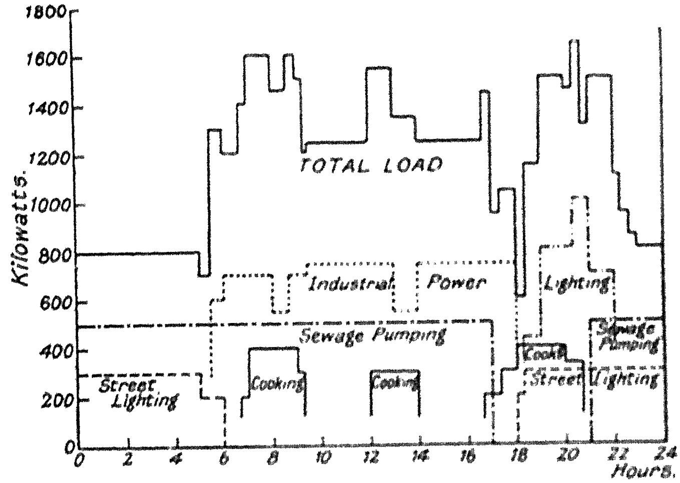


FIG. 51.—Load curve with excellent diversity and load factor.

267. Bibliography (see explanatory note, § 58).

A Study in Load Factors by Councillor Denny, *El. Rev.*, Vol. 86, p. 675, is based on an experiment made by the Glasgow Corporation, and shows clearly the improvement which can be effected in load factor by cultivating domestic demands for electricity (*see also* Chapters 26, 30).

Much information on maximum demand, diversity factor, and load factor is to be found (generally in relation to supply tariffs) in the *Journal of the I.E.E.* and in the electrical press.

CHAPTER 12.

ELECTRICITY COSTS AND TARIFFS.

268. 'Undertakers' and the Sale of Energy.—Where a public company or local authority, known in British law as 'undertakers,' is supplying energy under an 'order' within any 'area of supply,' it is generally cheaper to purchase from the undertakers rather than to generate from private plant (*see*, however, § 185), notwithstanding the fact that the undertakers must make a profit on their sales. For, in the first place, the supplier can lay down a large plant at a much lower capital cost per horse-power or kilowatt than a private person can lay down a small plant; secondly, he can keep his plant working at a better load factor (§ 264) than any private person, owing to the diversity of uses to which different consumers will put the power and the different times at which their various maximum demands (§ 265) will occur, *i.e.* the good diversity factor (§ 264) of the load. Even so, the actual works cost of generating a unit varies greatly in different undertakings, from about 0·9d. up to 8·4d. (Table 38, § 269); and the selling price varies accordingly. The most important item in the costs is the price of fuel (Tables 25, 26, § 194), and it is therefore often tacitly assumed that a hydro-electric plant will always be able to supply energy cheaper than a steam plant; this, however, is not necessarily the case, as the capital cost of water-power development is generally comparatively high (Table 35, § 216).

269. Analysis of Cost of Public Supply.—In order to realise the great variations in the working expenses of different undertakings, reference may be made to the tables published periodically by the *Electrical Times*, analysing the costs in hundreds of British power stations. There are certain general considerations applicable everywhere. In the first place, certain items of cost vary approximately with the output of the plant from time to time, *viz.* fuel, oil, water; engine-room stores; and (to some

extent) wages, repairs, and maintenance. Naturally, if the output increases greatly, the cost of these items *per unit generated or sold* drops somewhat, but on the whole it is fairly constant in any particular case; and in charging for energy supplied each consumer should pay his share of these charges according to his consumption. Owing to the absence of fuel charges, which may amount to from 30-60 % of the works cost of a steam station, the works costs of a water-power plant are generally lower. The other items of cost are independent of the output of the plant, *viz.* rent, rates, and taxes; management expenses; interest and depreciation; these involve the payment of a fixed sum, whether the output is large or small, more or less in proportion to the total size and capacity of the plant. As the output in units increases the cost of these items per unit diminishes; double the units, and the share of the cost of each is halved. Now, as the size of the plant ultimately depends on the maximum power required by the various consumers, it will be evident that each consumer should pay an annual sum sufficient to cover his share of these fixed charges, according to his demand, in addition to his share of the variable costs (*see also* § 260). In the case of hydro-electro plant nearly the whole of the costs are fixed, the capital charges being generally by far the most important; consequently in these plants the cost price of a unit varies almost inversely as the total output; if the plant is standing idle it is costing almost as much as when working continuously at full load, so that, in order to fill in the hollows in the load curve and improve the load factor, it pays to sell energy from such an undertaking at a very low price during certain restricted hours (§ 217). The various tariffs for the sale of energy are based on these two factors of variable costs and fixed costs.

Effect of Size of Plant and Load Factor on 'Works Costs.'—Although averages are notoriously unreliable, Table 38 may be found of some value. The figures therein have been calculated from the invaluable 'Tables of Costs and Records' which the *Electrical Times* has now published for many years. Typical plants of various sizes at various load factors have been taken, and the various items which make up the works costs (*i.e.* capital charges being excluded) have been averaged for each group; at the end of the table are given the highest and lowest costs of the 300 undertakings analysed in the paper mentioned. The average

TABLE 38.—*Works Costs per Unit (kWh) in Great Britain.*

Figures in italics relate to pre-war conditions, and figures in heavy type relate to the year 1922 (*see also* Table 26, § 194). Inconsistencies in this table are attributable mainly to differences between the conditions in the stations averaged, and to the fact that the italicised and heavy-face figures do not apply to the same groups of stations.

Plant Installed (Approximate).	Output per Annum.	Load Factor.	Fuel.	Oil, Waste, Water, Stores.	Wages.	Repairs and Maintenance.	Rent, Rates, and Taxes.	Management, Salaries, Office and Legal Expenses.	Total Works Costs.	
kW.	Millions of Units.	%.	Pence per Unit.							
300	*0·17*	*10*	*0·53*	*0·10*	*0·32*	*0·45*	*0·14*	*0·63*	*2·17*	
	0·21	**12**	**2·16**	**0·23**	**1·13**	**0·96**	**0·27**	**1·32**	**6·10**	
	0·24	*15*	*0·53*	*0·09*	*0·30*	*0·38*	*0·14*	*0·43*	*1·87*	
	0·30	**16½**	**1·73**	**0·11**	**0·72**	**0·86**	**0·20**	**0·75**	**4·39**	
	0·29	*19*	*0·52*	*0·06*	*0·26*	*0·28*	*0·10*	*0·36*	*1·58*	
1 000	*0·76*	*14½*	*0·51*	*0·05*	*0·25*	*0·28*	*0·12*	*0·33*	*1·54*	
	0·97	**15½**	**1·95**	**0·08**	**0·60**	**0·72**	**0·24**	**0·59**	**4·20**	
	1·0	*20*	*0·34*	*0·05*	*0·15*	*0·20*	*0·10*	*0·15*	*0·99*	
	1·4	**22¼**	**1·88**	**0·24**	**0·46**	**0·66**	**0·09**	**0·49**	**3·84**	
	1·6	*24*	*0·33*	*0·03*	*0·13*	*0·10*	*0·06*	*0·10*	*0·75*	
10 000	*11*	*17½*	*0·29*	*0·03*	*0·11*	*0·15*	*0·18*	*0·14*	*0·90*	
	9	**18**	**0·99**	**0·03**	**0·22**	**0·30**	**0·17**	**0·24**	**1·95**	
	12	*21*	*0·28*	*0·02*	*0·10*	*0·13*	*0·11*	*0·12*	*0·76*	
	11	**24**	**0·89**	**0·03**	**0·22**	**0·29**	**0·09**	**0·13**	**1·66**	
	13	*25*	*0·17*	*0·01*	*0·05*	*0·11*	*0·05*	*0·09*	*0·48*	
35 000 to 45 000	**32½**	**17½**	**0·81**	**0·01**	**0·19**	**0·31**	**0·36**	**0·27**	**1·98**	
	42	*21*	*0·21*	*0·01*	*0·08*	*0·08*	*0·15*	*0·10*	*0·63*	
	46	**24½**	**0·57**	**0·01**	**0·13**	**0·17**	**0·12**	**0·11**	**1·13**	
130 000	**145**	**21½**	**0·56**	**0·02**	**0·17**	**0·23**	**0·17**	**0·12**	**1·28**	
100	*0·06*	*10*	*1·29*	*0·13*	*0·63*	*0·09*	*0·16*	*0·99*	*4·10*	Highest
292	**0·17**	**12¾**	**3·90**	**0·19**	**1·61**	**1·15**	**0·08**	**1·14**	**8·07**	
7 500	*14·6*	*29*	*0·19*	*0·01*	*0·04*	*0·03*	*0·03*	*0·02*	*0·32*	Lowest
9 000	**10·2**	**20**	**0·38**	**0·01**	**0·17**	**0·13**	**0·08**	**0·12**	**0·89**	

load factor of the whole number is 18·6 % (20 % in 1915),* and the average works cost is 3·07d. / kWh (0·87d. in 1915). Data relating to some 50 stations have been used in compiling Table 38. As would be expected, the larger the undertaking, the lower are the costs; and the higher the load factor for any given size of plant, the lower are the costs. Fuel generally accounts for one-third to one-half of the total works cost in England (*cf.* Tables 25, 26, § 194). In such countries as India, fuel generally costs proportionately more, especially where it has to be carried into the hills; labour may cost somewhat less, but supervision costs more.

270. The Sale of Electrical Energy by Meter; Flat Rate.—The only method of ascertaining the value of the supply, and charging for it, which is readily understood by the public, is that of sale by meter at a fixed price or 'flat rate' for each and every unit consumed; consequently this method is in more general use than any other system of charging. It has the disadvantage, from the central station point of view, that it does not encourage the most profitable type of consumer, *i.e.* the consumer who, by using energy when the average demand is small, is most profitable to the central station (directly), and hence of greatest benefit (indirectly) to the consumers as a whole. The supply meter registers on its dials the actual number of units supplied; sometimes these units are charged for at a flat rate of (say) 2d., 4d., or 6d.; sometimes discounts are given either to very large consumers or to all who pay prompt cash; again, two meters are sometimes installed, one for registering energy used for lighting, and the other for registering energy used for other purposes, different rates being charged in the two cases (§ 275, *A* and *B*). The technical features of various types of supply meters are discussed in §§ 113-117, and the correct method of reading meter dials is explained in § 113. Meter testing is dealt with in Chapter 40. Most supply companies arrange to test meters specially on consumer's request, the cost of the test being borne by the consumer if the meter proves to be accurate within the limits laid down by law, *i.e.* if the error does not exceed ± 3 % between $\frac{1}{10}$ full load

* The lower average load factor in 1922 compared with 1915 is probably due to some of the generating plant installed for war service being lightly loaded during the post-war industrial depression; the kWh / annum increased greatly during the war (§ 197) and the load factor will rise as industrial conditions improve.

and full load and under normal supply conditions in meters of less than 3 A capacity, or ± 2 °/₀ in larger meters.

271. Minimum Quarterly Charge.—The Electric Lighting Orders granted by the Board of Trade since 1890 generally provided for a minimum quarterly charge to consumers, for any amount up to 20 kWh, of twenty times the authorised maximum price per unit. The intention of this provision was to ensure to undertakers a reasonable return from each consumer in respect of the capital expenditure incurred to enable the desired supply to be available at all times to all consumers. In the case of large undertakings supplying industrial districts, lighting consumers now represent so small a fraction of the total load that it is generally possible to supply them without insisting upon payment of a minimum quarterly charge. It should be borne in mind, however, that every consumer may justly be expected to yield a fair return upon the capital expenditure involved in rendering supply available to him, and that this capital expenditure has increased (actually, though not relatively; Table 25, § 194), due to the general rise in costs, whereas the use of high efficiency incandescent lamps and the operation of the Summer Time Act (Chapter 25) have reduced greatly the energy consumption of the average lighting installation. These factors bear particularly heavily upon the smaller electricity undertakings, which mainly supply a lighting load and operate at low load factor, and in such cases it is economically essential to impose a minimum quarterly charge or to secure by other means a reasonable return for the facilities provided.

Domestic and shop-lighting consumers are the ones principally affected by minimum-charge regulations and that mainly during the summer months. In typical cases, the occupiers of small houses and flats with, say, 400 W of lamps installed, consume about 30 kWh during the 3 months April 1 to June 30 with Summer Time in operation. Circumstances vary, but in few, if any, cases would the revenue from the sale of 30 kWh cover the legitimate standing charges on a 400 W installation in addition to the actual cost of the energy consumed, even when the price per unit is 50 °/₀ above the pre-war figure. To allow for this, the Electricity Commissioners recommend that a minimum quarterly charge be allowed on the following basis :—

(*a*) In respect of each of the two winter quarters, for any amount up to 15 units, fifteen times the authorised maximum price per unit ;

(*b*) In respect of each of the two summer quarters, for any amount up to 10 units, ten times the authorised maximum price per unit.

272. Tariffs Based on Maximum Demand.—(*a*) *Fixed*

Price per Kilowatt.—The considerations discussed in §§ 259, 270 have led to the introduction of various tariffs based entirely or mainly on the maximum demand of each consumer, with the twofold object of increasing the profits of the undertaking and diminishing the price per unit paid by the consumer. These two apparently inconsistent aims can only be reconciled when the result of such a tariff is both to enhance the output and improve the load factor of the station; the latter consideration involves the encouragement of the use of power for fans, motors, heating, etc., during hours when lights are not required.

Whereas lighting was the main, if not the only duty of the early central stations, and industrial power has become the principal factor during recent years, it is now realised that domestic applications (other than lighting) are capable of being developed so as to constitute the greatest load on the station, as well as the most desirable from the standpoint of high average load factor; (*see El. Rev.*, Vol. 86, p. 675).

A special indicator is used to record the maximum demand (§ 117). A warning device or 'current limiter' is sometimes added, which rings either a bell or a buzzer when a predetermined maximum is reached, or, alternatively, interrupts the supply at intervals of a second or so.

The simplest tariff based on maximum demand is that which makes a fixed charge per kW of maximum demand, regardless of the consumption in kWh and of the purposes to which the current is applied. This charge may be so much per annum per kW, this being a common basis of charging where industrial loads are supplied from hydro-electric stations or from overland power transmission systems. Alternatively, it may be per quarter, per month, or per week in the case of small power users and for domestic supply. In the latter case the charge frequently takes the form of a fixed weekly payment per lamp of specified type and candle-power (§ 275, *E*). Obviously this is simply a fixed charge per week per kW of maximum demand, though it is referred to a basis more easily understood by, and hence more appealing to, the class of consumer to whom it applies, *viz.* artisans, tenement dwellers, and so on. So far as the authors are aware, this is the only form in which the 'fixed charge per kW' tariff is applied in Great Britain, but this form of tariff is used considerably abroad in connection with heavy power supply from

hydro-electric stations. In the latter case, the load factor of the industry concerned is known, or can be determined with reasonable accuracy, so that, in making a fixed charge per month per kW, the supply engineer is really making simply a lump charge for a certain number of units at a price per unit which he considers profitable. In street lighting contracts a fixed charge per lamp per annum is frequently agreed upon, but the total annual consumption is then known within very close limits, and the remarks in the previous sentence apply with particular force. In domestic supply, however, the load factor is a much more variable factor, and there is considerably greater risk of current being used recklessly. The use of a 'current limiter,' cutting off supply or actuating a trembling contact in the event of the demand exceeding a predetermined maximum, prevents more lights being used at once than are contracted for by the consumer's payment. On the other hand, the cost of a limiter is at least comparable with that of a meter. As regards preventing lamps being kept alight needlessly, this can be done more or less satisfactorily by making the consumer pay for lamp renewals and by refusing to renew contracts in the case of flagrant offenders. The longevity and cheapness of modern filament lamps makes the 'pay-for-renewals' arrangement less effective than formerly as a safeguard against current wastage.

In St. Marylebone (London), where the 'fixed charge per lamp' principle is applied in artisans' dwellings, the charge is calculated in the case of kitchens and living-rooms so that if the consumer used his lamps day and night the price obtained per unit would be from 0·7d. to 1·2d. The actual price is 7d. per week per 60 W (or 6d. per 30 W) tungsten lamp for living-rooms; and 4d. per week per 30 W (3d. per 20 W) metal filament lamp, or 2d. per week per 8 c.p. carbon filament lamp for bedrooms. If the living-room lamp be used 5 hrs. a night, this charge corresponds to about 3·4d. per kWh in the case of 60 W lamps, and 5·7d. per kWh if a 30 W lamp be used. It should be noticed that the fixed charge covers lamp renewals, and a sum calculated to write off within a reasonable period the capital spent on wiring.

(b) *Standing Charge plus Low-unit Charge.*—A more effective method of preventing waste, and certainly a more rational tariff, consists in charging a fixed annual sum per kW of maximum demand, plus a small additional charge per kWh actually consumed, as registered by meter, but still regardless of the purpose to which the current is applied. This method of charging, which is practically the 'telephone' system mentioned in § 273, involves

providing a meter, which it is the chief object of the previous tariff to avoid in the case of very small consumers. The present tariff encourages the long-hour consumer, for every additional unit used adds little to the bill, and reduces the *average* price per kWh. Suppose, for instance, a purely lighting installation, with a maximum demand of 2 kW, to be working under this tariff; the owner could introduce a motor or other apparatus, also taking 2 kW, and so long as it was not used during lighting hours, his fixed annual charge would be unaltered, the maximum demand remaining at 2 kW. He would only have to pay for the additional units used by the motor at the low rate of charge presupposed (§ 275 *D*).

The fixed or standing expense incurred by keeping the supply system ready for service, includes the interest and redemption charges on the capital investment, rents, rates, insurance, etc., and a proportion of the wages and coal bills. Hitherto, where maximum demand tariffs have been used, it has been customary to recoup the standing expenses by a fixed charge per kW of maximum demand, but it has been shown by J. R. Blaikie (*Jour. I.E.E.*, Vol., 59, p. 701) that there is much to be said in favour of different fixed charges for industrial and residential consumers. Large factory loads, demanding supply during well-defined hours 6 days a week, involve much lower capital charges per kW and considerably lower coal and wages costs (apart from the saving due to higher load factor) than do small residential demands which may require supply at any time, throughout the week (*see*, however, the note in § 271 regarding the favourable effect of wholesale utili-ation of electricity for domestic purposes). Proposals for tariffs discriminating between consumers requiring supply for 7 days a week and those requiring supply for 6 days a week are given in the paper *loc. cit.*

Wright's System.—In this older system of charging, the consumer pays a high price per unit metered until his consumption corresponds to 1 (or 2) hrs.' daily use of his maximum demand during the period for which the account is rendered; this charge is equivalent to the fixed charge in the preceding paragraph; for all units used over this amount he pays at a low rate. For example, if the maximum demand recorded by the indicator (§ 117) is 2 kW, then an average of 2 units a day (*i.e.* 180 kWh per quarter of 90 days), equal to 1 hrs.' use per diem of the maximum demand, must be paid for at the high rate. If the actual consumption as shown on the meter averages 5 units a day during the period in question, the balance, or 3 units a day, will be paid for at the low rate.

Restricted Hour Tariffs.—Methods of charging which depend on the time at which the maximum demand occurs have also been

tried, with a view to improving the diversity factor of the power station. In this case two-rate meters (§ 116 (ii)) are used, in which a clock or time switch regulates the hours at which each tariff is operative. In many places the introduction of a two-rate tariff has led to important increases in demand during off-peak periods.

273. **Rateable Value; Glasgow, Metropolitan, Telephone, and Point-five Tariffs.**—A detailed discussion of all the chief types of residence tariffs, *i.e.* charges for electricity supplied for domestic purposes, is to be found in a paper delivered some years ago by Mr. A. H. Seabrook (*Jour. I.E.E.*, Vol. 48, pp. 376 *et seq.*). That author laid stress upon the fact that the Hopkinson principle (of making distinct charges for M.D. and kWh consumed, to cover standing and running costs respectively) is the only scientifically correct basis of charge, though it is by no means universally applied, owing to the difficulty of framing a simple tariff thereon. Mention has already been made (§ 272) of the fixed charge per kW or 'contract demand' tariff and of the Wright maximum demand system. Other tariffs based on the Hopkinson principle and finding more or less extensive application in Great Britain are the rateable value tariff, the Glasgow system, the Metropolitan system, and the telephone system.

The *rateable value* tariff consists of a fixed annual payment (based upon the rateable value of the consumer's premises) supplemented by a low charge per kWh of metered consumption. This system of charging is generally known as the *Norwich system* from the town of its origin. Consumers in private houses, may, for example, have the option of paying a flat rate of 4½d. per kWh for all purposes, or, alternatively, of paying 12 °/ₒ on the rateable value of the premises, plus 1d. per unit; in the case of business houses the fixed charge is based on the lamps installed, and may be, say, 5s. to 7s. 6d. per lamp per annum.

According to *The Practical Electrician's Pocket Book,* the average annual consumption of consumers taking domestic supply under rateable value tariffs in 1922 is given in the table on p. 378.

Though the rateable value tariff may be held to have justified itself in practice, it is obviously an empirical tariff; there is no definite relation between the rateable value of premises and the maximum demand of the electricity consumer occupying those premises. The percentage of the rateable value taken as the fixed

Town.	kWh per £1 R.V.	Town.	kWh per £1 R.V.
Blackpool	35	Sheffield	43
Bradford	42	Stafford	15·6
Carlisle	45	Sutton Coldfield	21
Chester	64	Uxbridge	28
Derby	30	Watford	38
Dewsbury	23	West Hartlepool	48·6
Halifax	26	Winchester	50·2
Harrogate	46	Wolverhampton	57·2
Leigh	65	Wrexham	26
Liverpool	34		

charge differs from town to town (*see also* § 275, *F*). The following are a few cogent arguments from an article discussing the characteristics of the rateable value tariff:—

The most tempting feature of the rateable value tariff, from the central station point of view, is its simplicity. The fundamental assumption is that rateable value is a reasonably accurate measure of the electricity-consuming capacity of private premises, and the fundamental weakness of the system is that it is not necessarily or even generally anything of the kind. Houses of similar size and quality shelter families of very different sizes and habits, so that rateable value bears neither theoretical nor actual relationship to the current consumption of a household. In some cases the percentage charge on rateable value is increased, and in other cases decreased, as the rateable assessment increases. In any event, if a different percentage of R.V. is to be charged in the case of different-sized houses (as seems desirable), and if allowance is to be made for the effect of specially large or small gardens on rateable value (as seems essential), the R.V. tariff at once loses its merits of simplicity and power of being easily understood by the layman. The method generally employed (at the time of initiating the new tariff) in determining the percentage of rateable value to be taken as the fixed charge, is to analyse previous accounts, and see what percentage of rateable value will, in conjunction with, say, ½d. per unit, give the same revenue from lighting as the previous flat rate (say, 4d. a unit). This amounts to securing the station's revenue and supplying all additional units at ½d. It is a simple, if tedious, method of arriving at a suitable *average* percentage on rateable value, but there is nothing to secure (1) that this percentage will not be far wide of the mark in individual cases; and (2) that the percentage decided by reference to previous accounts will be at all suitable under the new conditions which it is desired to bring about by the new tariff. Generally the percentage charge is 10, 12½, or 15 % on rateable value, but it makes a considerable difference to consumers, and so, ultimately, to the station's prospects, which percentage is adopted. The average price per kWh fluctuates enormously with rateable value and with total consumption per annum, wherever the rateable value tariff is applied; this cannot be fair to either supply authority or consumer. Perhaps the most disturbing feature is the considerable difference in average price per unit paid by consumers taking the same amount of energy, but using it in houses of different rateable value. Nor can this discrepancy be justified by attributing it to differences in load factor, for sometimes the difference is in one direction and sometimes in the other. District, size of garden, and

assessor's whim are a few of the factors determining the rateable value. Number and position of windows, nature of surroundings, number and habits of household are factors influencing the consumption of electricity for lighting and other domestic purposes. Where is the connecting link between these groups of factors? On the average for a whole district the rateable value tariff may be equitable, and in most cases where it is working it *is* equitable as between supply authorities and consumers as a body; but is this altogether unconnected with the fact that the tariff has only been in vogue a few years, and that when it was put into force it was deliberately arranged to give what might be called 'average equity'? In other words, is not the tariff very largely artificial—with just that basis of reason sufficient to make it plausible and workable for the nonce? The rateable value tariff must already be responsible for grave anomalies between the current consumption and bills of individual consumers, and such anomalies cannot be good for the development of the industry as a whole. The maximum demand system in a modified form is, in the writer's opinion, the best and fairest possible. Every consumer is entitled to special consideration of his case, for, after all, it is to meet the electrical engineer's difficulties and limitations that any departure at all from the flat rate is required. It is, at this date, quite easy to estimate what will be the average maximum demand for any proposed equipment, and so to determine a fixed charge which shall be fairer to the consumer than the R.V. charge can be, whilst being, for the district as a whole, equally satisfactory to the station (*El. Rev.*, Vol. 77, pp. 443 *et seq.*).

The *Glasgow system* charges a fixed number of hours' use of the M.D. at a primary rate, and all further consumption at a lower secondary rate. When the system was first enforced in Glasgow, it was found that the average domestic consumer used his lighting M.D. for 800 hrs. per annum, so the tariff charged 800 hrs.' use of the M.D. at 3d. per kWh, and all additional units at 1d. The system is only a slight modification of the Wright system (§ 272), and, like the latter, it overcharges the consumer for any heating and cooking consumption unless the latter be metered separately.

The *Metropolitan system* consists of a fixed primary charge (based on the kW capacity and nature of lighting and other apparatus installed) plus a certain charge per kWh till the amount of this charge equals the primary charge. Thereafter all units are supplied at a lower price. For example, the fixed primary charge may be £5 per annum, the first energy charge 2d. and the second 1d. per kWh. Then the consumer's minimum bill is £5; if he uses 600 kWh per annum he pays a further £5 for them, *i.e.* a total of 4d. per kWh on the average; thereafter he obtains additional units at 1d. Under these conditions the average price is: 8d / kWh for 200 kWh per annum, 4d. for 600 kWh, 2·8d. for 1 000 kWh, 1·9 for 2 000 kWh per annum, and so on. This system of charging does away with double metering

and double wiring. The chief object of the two rates of charging for energy seems to be that consumers using only small domestic appliances pay for all current at the lighting rate, whereas if they install heaters or cookers they get on to the lower energy rate, to which they are entitled.

The *telephone system* was so named because it consists (like the telephone charges formerly in force in this country) of a fixed annual payment in advance, plus a small unit charge for service actually utilised, *i.e.* per kWh consumed. The fixed charge is based on a certain percentage, say, 70 °/₀ of the connected lighting load, not counting convenience or decorative lighting, and not counting wattage installed for other than lighting purposes. The secondary charge is low, say 1d. or 1½d. per kWh. The standing charges are based solely on the lighting installation, and it is insisted that only electric lighting be used on the premises. By exempting 'convenience' lamps from standing charges, the installation of such lamps is not checked. The system encourages liberal and long-hour consumption of energy, is easy to understand, and needs only a single meter, whilst being applicable to all classes of domestic supply. The advantages and working of the system are dealt with fully in Mr. Seabrook's paper (*loc. cit.*).

Point-five tariffs have as their object the encouragement of electric heating and cooking. As matters stand at present, any system of charging can claim to be a point-five tariff, so long as it provides additional units for heating and cooking at 0·5d. per kWh. This charge may be, and generally is, supplemented by a fixed charge or minimum payment in some form or other, so that the average price per kWh is generally considerably higher than 0·5d.; but, as explained in Chapter 26, the important point is that the charge which varies with the use of the apparatus, *i.e.* the energy charge for 'additional' units, be low, so as to encourage liberal consumption and make the wastage of a few units of negligible importance to the consumer; the central station can afford to supply them at low price, once the standing charges have been covered.

274. Tariffs taking Power Factor into Account. — The ill-effects of low-power factor in A.C. circuits have been discussed in § 155. As these effects increase the costs of producing and distributing a given quantity of energy (kWh as distinct from kVAh, § 154), it is justifiable to impose upon the consumer a

supplementary charge if the power factor of his load is lower than unity, the amount of this charge being greater, the lower the power factor. The primary function of any such charge is naturally to penalise low-power factor and so give the consumer a monetary inducement to avoid it. It is not in the interests of the supplier to *sell* 'wattless energy,' which is useless, but to stimulate consumers to improve the power factors of their loads. If *leading* wattless energy is beneficial to the P.F. of the system as a whole it may be supplied gratis (or even with a bonus), but, under the ideal conditions of unity power factor, leading wattless energy is as objectionable an addition as lagging current (§ 153).

Any tariff taking into account the P.F. of the load involves *either* assuming an average value for the power factor (to which assumption the consumer may reasonably object); *or* the measurement of the power factor either directly (§ 111) or indirectly by the use of watt-hour and voltampere-hour meters (§§ 115, 116). In the case of large installations the cost of two or three metering instruments can be afforded, but this is not so where small consumers are concerned, and these are often the worst offenders in respect of low-power factor.

One method of penalising low-power factor is to charge for the true energy (kWh) metered according to a sliding scale, the price per kWh increasing as the P.F. decreases. This method demands that the supplier should know the cost per kWh delivered at various power factors (which varies with the location of the consumer because of the transmission losses occasioned by low P.F., § 155); also, the method depends upon the consumer accepting the estimated value of his power factor, since the actual P.F. generally varies widely and continuously, as can be seen from the chart of a recording P.F. meter.

A better method of taking power factor into account consists in making a fixed charge per kVA of maximum demand (instead of per kW, § 272 *b*) plus a unit charge per kWh consumed. If the supply voltage be constant, the maximum kVA can be measured by a maximum current indicator calibrated in kVA, *i.e.* by an ampere-hour meter (§ 114) fitted with a maximum increment indicator on the principle of the Merz demand indicator (§ 117). Unfortunately, variation in P.F. generally involves appreciable variation in delivered voltage (§ 155), and it is then necessary to determine the maximum kVA from the maximum kW by dividing the latter by the power factor. This involves a third measuring instrument (in addition to the maximum kW and kWh meters), which must be either a recording P.F. meter or a wattless kVA (or sine) meter, §§ 110, 116 (iv). In the latter case the quotient (wattless kVA) / kWh gives tan ϕ, whence cos ϕ is obtained by reference to tables. In its more accurate form this method of charging is fairly complex and, even then, it allows only for the increase in fixed costs occasioned by low-power factor, and not for the increase in running or working costs. Though the increase in standing charges is the main factor, the other is not negligible (§ 155).

Professor Arno (Milan) has devised a special meter, the reading of which is determined by two-thirds of the kWh consumption and one third of the kVAh consumption. The consumer is charged so much per composite 'unit' as thus recorded, hence the actual charge per kWh increases as the kVA consumption rises (*i.e.* as the P.F. decreases). Though reasonable justification for this method of charging can be demonstrated on paper, the system is obviously sufficiently arbitrary to be open to question by consumers.

Many other tariffs * have been devised for taking power factor into account, but there are so many factors involved that costly metering equipment and elaborate accountancy are required to arrive with certainty at a close approximation to the equitable charge. For most practical purposes, if the consumer will consent to the arrangement in his supply contract, it is sufficiently accurate to use the maximum demand system (§ 272 *b*), correcting the indicated maximum demand according to the formula: $kW_c = kW_i \times P / Q$; where kW_c = corrected max. demand used to calculate the standing charge, at so much per kW; kW_i = actual max. demand as indicated by the demand indicator; P = assumed basic or standard power factor, say 0·7, 0·8, or 0·85, according to circumstances; and Q = consumer's load factor as measured periodically, at the undertaker's discretion, under conditions of normal load. The standing charge per kW thus varies inversely with the consumer's power factor and the unit charge per kWh is the same for all power factors. If a fairly low value of P (say 0·8) be taken as the basic power factor (the standing charge per kW being adjusted accordingly) the average consumer will be able to maintain a power factor higher than P, thus securing a reduction in the charge per kW. This amounts to offering a bonus for high-power factor, rather than imposing a penalty for low-power factor, and is to be recommended for psychological reasons.

275. Actual Tariffs in the United Kingdom: Examples of Charges.—It would serve no useful purpose to attempt anything like a complete statement of the great variety of tariffs actually in force in this country, but the following typical examples are interesting and instructive:—

Note.—The prices given below are practically pre-war tariffs. In most places the charges are now (1923) at least 50 % higher and in some of the towns men-

* *See* 'The Improvement of Power Factor,' by Gisbert Kapp, *Jour. I.E.E.*, Vol. 61, p. 89; and, for American practice, *Nat. El. Light Assoc. Bull.*, Sept., 1921, pp. 520, 551.

tioned the tariff system itself has been changed. On the other hand, the examples given are representative of the principal tariffs used in Great Britain, and the general purpose of the examples is better served by retaining the old prices, which were on a stable basis, than by inserting prices which are abnormal and unstable. In most places the charges for electricity supply have fallen greatly from the war level, and it is not too much to hope that economies resulting from the broader policies now followed in generation and distribution, will compensate for higher coal and labour costs, thus making possible tariffs as low as those ruling before the war.

Section 22 (1) of the Electricity (Supply) Act, 1922, repealed Subsection 2 of Section 31 of the schedule to the Electric Lighting (Clauses) Act, 1899, under which a consumer had hitherto had the option of requiring undertakers to charge him for the actual amount of energy supplied or for the electrical quantity contained in the supply. The effect of this repeal was to remove what had been an obstacle to the general adoption of multi-part tariffs, and thus to permit tariffs to be introduced suitable for the varied demands on an undertaking and for encouraging the more extensive utilisation of electricity. If, however, the consumer and the undertakers had entered into an agreement as to a special method of charge, a course expressly provided for by the Act of 1899, and that agreement was for a definite period and allowed a definite length of notice to be given before either party could terminate it, it is practically certain that the contract would have been held good. The provision for termination by one month's notice was "in the absence of an agreement to the contrary." The point is of importance as the alteration in the law referred to holds good only in the United Kingdom and not in overseas countries which have followed British law.

A. *Flat Rates by Meter* (§ 270).

(i) St. James and Pall Mall (London). Heating, 1½d. a unit.
(ii) Winchester. Lighting, 5¾d. a unit.
(iii) Falkirk. Lighting, 5d. a unit.
(iv) Prescot. Lighting, 4d. a unit. Power, 1d. a unit.
(v) Reading. Heating and cooking, ½d. a unit, where current is also taken for lighting.
(vi) Burslem. Cooking, 1d. a unit, if premises lighted throughout electrically.
(vii) Manchester. Lighting, 3¾d. a unit. Domestic power, 1¼d. a unit.

B. *Meter Rates with Discounts* (§ 270).

(viii) St. James and Pall Mall (London). Lighting, 6d. a unit first 4 000 units per annum; 4d. thereafter.
(ix) Chertsey. Lighting, 6½d. a unit. Power, 2½d. a unit. Less ½d. in each case for cash.
(x) Malvern. Lighting, 7d. a unit. Power, 4d. a unit. Less 5 °/ₒ in each case for cash.
(xi) Reading. Lighting: up to 20 units a quarter, 8d. a unit (minimum charge 13s. 4d.); for next 480 units up to 500 units a quarter, 4½d. a unit; then, up to 1 000 units a quarter, 4d. a unit; then, up to 2 000 units a quarter, 3½d. a unit; and further reductions for greater quantities.
(xii) Burslem. Power and heating: up to 250 units a quarter, 2d. a unit; then 1½d. a unit up to 500 units; then 1d. a unit. (Also special bulk rates.)

(xiii) Manchester. Power: less than 200 units per quarter per measured E.H.P., 1½d. a unit; then 1¼d. up to 299 units per E.H.P. per quarter; then 1d. up to 399 units per E.H.P. per quarter, etc., finally reaching 0·7d. a unit.

(xiv) Liverpool. Lighting: up to 3 000 units a quarter, 3½d. a unit; then 3d. a unit up to 10 000 units; then 2½d. a unit. Power, 2d., 1½d., and 1d. a unit (within same range as lighting).

C. *Maximum Demand* (§ 272).

(xv) Winchester. Lighting, 7d. a unit first hour's use, 4d. second hour's use, 2d. afterwards. Power, 3½d. first hour, 1½d. second hour, ½d. afterwards.

(xvi) Falkirk. Power, 2½d. a unit first hour, 1½d. afterwards.

(xvii) Burslem. Lighting, 7d. a unit for 91 hrs.' use of M.D. per quarter, and 2d. a unit afterwards, the average not exceeding 5d, a unit. (Alternative, 5d. flat rate.)

D. *Fixed Charge per H.P. or kW + Charge by Meter* (§ 272).

(xviii) St. James and Pall Mall (London). Power, 7s. 6d. per rated H.P. per quarter, plus 1d. a unit.

(xix) Dartford. Lighting, £12 per kW for first kW demand; £9 per kW for higher demand, plus 1d. a unit.

(xx) Falkirk. Power (above 20 H.P. installed), £2 10s. per H.P. maximum demand, plus ¾d. a unit; less 10 °/₀ on ¾d. rate for each 100 000 units taken per annum.

(xxi) Reading. Power: exceeding 3 kW at 400 V continuous current, £1 a quarter per kW, plus ¾d. a unit up to 10 000 units a quarter, and ½d. a unit beyond; not exceeding 3 kW, 13s. 4d. a quarter minimum charge, plus 1½d. a unit for consumption in excess of 20 units.

(xxii) Manchester. Lighting, £7 per annum per kW M.D., plus 1½d. a unit. Power, if over 600 units per E.H.P. per quarter, £1 5s. per E.H.P. demand per quarter, plus ⅓d. a unit.

(xxiii) Liverpool. Lighting, £2 per quarter per kW M.D., plus 1½d. a unit. Power, £1 10s. per quarter per kW M.D., plus 0·4d. a unit.

E. *Fixed Charge per Lamp* (§ 272).

(xxiv) Carmarthen. Cottage lighting, 4d. a week per 30 W lamp.

(xxv) Dunster. 50 c.-p. lamp, 3s. 6d.; 25 c.-p., 2s. 6d.; 16 c.-p., 1s. 10d. a quarter.

F. *Rateable Value System* (§ 273).

(xxvi) Winchester. Lighting, 3s. per £1 rateable value, plus 1d. a unit.

(xxvii) Carlisle. Domestic tariff, 12½ °/₀ on rateable value, plus ½d. a unit.

(xxviii) Manchester. Domestic power, 12½ °/₀ on rateable value, plus ½d. a unit for all purposes; provided that domestic appliances other than lamps be installed to the extent of 2 kW in houses of rateable value not exceeding £30; 3 kW, not exceeding £50; 4 kW, exceeding £50 rateable value.

(xxix) Liverpool. 3½ °/₀ per quarter (2½ °/₀ for private houses only) on rateable value, plus 1d. a unit for all purposes.

G. *Flat Rate subject to Specified Minimum Load Factor.*

(xxx) Brompton and Kensington E.S. Co. (London). Motors exceeding 4 H.P., 1d. a unit, subject to minimum load factor of 11·41 %. Sign lighting, 2d. a unit, subject to minimum load factor of 20 % and 3 years' contract.

H. *Restricted Hour Rates* (§ 272).

(xxxi) Dewsbury. Power, $\frac{3}{4}$d., $\frac{5}{8}$d., $\frac{9}{16}$d., or $\frac{1}{2}$d. a unit, according to quantity, plus rental for time switch.

(xxxii) Manchester. Power, 1d. a unit (subject to minimum of 7s. 6d. a quarter), provided no current is taken between 4 P.M. and 6 P.M. in November, December, January, and February.

I. *Meter Rents, etc.*

(xxxiii) St. James and Pall Mall (London). Meter registering up to 1 kW, 2s. 6d. a quarter; from 1 to 5 kW, 5s.; over 5 kW, 7s. 6d.

(xxxiv) Reading. Nil.

(xxxv) Burslem. 1s. a quarter.

(xxxvi) Manchester. Restricted hour time switch, 2s. 6d. a quarter.

EXAMPLE OF CHARGES BY VARIOUS TARIFFS. — By way of practical example, the cost of these tariffs may be worked out for a hypothetical installation containing a variety of apparatus. In this connection it must be remembered that the tariffs mentioned above are not the only ones available in some of the places concerned; in some cases the full tariff schedule is very complex, so that the actual charge made might vary considerably from the following estimates. Assume the installation data to be as follows:—

(*a*) Fifty 40 W lamps = 2 kW or 2 units per hr. if all alight simultaneously.
Maximum demand, 7 to 9 P.M., 1·7 kW.
$2\frac{1}{2}$ hrs.' average use of all lamps per day.
Units per day, 3 in summer, 7 in winter.

(*b*) Cooking equipment—one 3 kW oven; one $1\frac{1}{2}$ kW grill; 3 1 kW hot plates.
Maximum demand, $7\frac{1}{2}$ kW at any time between 7 A.M. and 9 P.M.
Working hours, 14-16 hrs. a day intermittently.
Units per day, 15, average all year round.

(*c*) Four heaters of $\frac{1}{2}$ kW each = 2 kW.
Maximum demand, 2 kW any time between 7 A.M. and midnight (winter only).
Working hours, 18 per diem for 7 months.
Average load, $1\frac{1}{2}$ kW.
Units per day, 27.

(*d*) One 10 B.H.P. motor, used for industrial purposes, taking 9 kW at full load.
Working hours, 8 A.M. to noon and 1 P.M. to 6 P.M = 9 hrs. per diem.
Maximum demand, 9 kW at any time during those hours.
Average load, 5 kW or 5 units per hr.
Units per day, 45 all the year round.

(e) *Whole installation.*

Total load connected, $2 + 7\frac{1}{2} + 2 + 9 = 20\frac{1}{2}$ kW.

Maximum demand. The lights and the large motor do not overlap, so the maximum demand will be the sum of the M.D. of motor and cooking apparatus in summer, plus heaters in winter, *i.e.* $16\frac{1}{2}$ kW in summer and $18\frac{1}{2}$ kW in winter.

The units consumed will be:—

	Per Month.		Per Annum.
	Summer.	Winter.	
Lighting per day 3 or 7	90	210	1 800
Cooking ,, 15	450	450	5 400
Heaters ,, 27	—	810	5 670 (7 months)
Motors ,, 45	1 350	1 350	16 200
Total	1 890	2 820	29 070

The annual bill on these hypotheses, subject to the limitations noted and based on the tariffs specified below, will be as follows:—

(i), (viii), and (xviii) combined.	£	s.	d.
Cooking and heating, 11 070 units at $1\frac{1}{2}$d.	69	3	9
Lighting, 1 800 units at 6d.	45	0	0
Motor, 10 × 7s. 6d. fixed, plus 16 200 units at 1d.	71	5	0
Meter rent: lighting, 5s.; heating and cooking, 7s. 6d.; motor, 7s. 6d. a quarter	4	0	0
Average price per unit, 1·56d.	189	8	9

(iv).	£	s.	d.
Lighting, 1 800 units at 4d.	30	0	0
Cooking, heating, and motor, 27 270 units at 1d.	113	12	6
Average price per unit, 1·19d.	143	12	6

(v), (xi), and (xxi) combined.	£	s.	d.
Cooking and heating, 11 070 units at $\frac{1}{2}$d.	23	1	3
Lighting, 20 units at 8d. = £0 13 4			
,, 430 ,, $4\frac{1}{2}$d. = 8 1 3			
4 × 450 units per quarter = 4 × £8 14 7	34	18	4
Motor, 9 × £1 fixed charge, plus 16 200 units at $\frac{3}{4}$d.	59	12	6
Average price per unit, 0·97d.	117	12	1

(vi), (xii), and (xvii) combined.

				£	s.	d.
Cooking, 5 400 units at 1d.				22	10	0

Power and heating—Summer, 4 050 units a quarter.
Winter, 6 480 „ „

	Summer. £	s.	d.	*Winter.* £	s.	d.	£	s.	d.
500 units at 2d.	4	3	4	4	3	4			
500 „ $1\frac{1}{2}$d.	3	2	6	3	2	6			
Balance at 1d.	29	11	8	53	4	2			
	36	17	6	60	10	0	97	7	6

Lighting, 91 hrs.' use of M.D., 91 × 1·7, or 155 units per quarter—

					£	s.	d.
155 units at 7d. .	£4	10	5				
115 „ 2d. .	0	19	2				
	£5	9	7	per summer quarter × 2	10	19	2
155 units at 7d. .	£4	10	5				
475 „ 2d. .	3	19	2				
	£8	9	7	per winter quarter × 2 .	16	19	2
Meter rents (three at 1s. per quarter)					0	12	0
Average price per unit, 1·23*d*.					148	7	10

(vii) and (xiii) combined.

					£	s.	d.
Lighting, 1 800 units at $3\frac{3}{4}$d.					28	2	6
Cooking and heating, 11 070 units at $1\frac{1}{4}$d.					57	13	$1\frac{1}{2}$
Per quarter per E.H.P.							
Motor, 200 units at $1\frac{1}{2}$d. . . .	£1	5	0				
100 „ $1\frac{1}{4}$d. . . .	0	10	5				
$37\frac{1}{2}$ „ 1d. . . .	0	3	$1\frac{1}{2}$				
$337\frac{1}{2}$ units	£1	18	$6\frac{1}{2}$	(× 4 × 12) . .	92	10	0
Average price per unit, 1·47*d*.					178	5	$7\frac{1}{2}$

(vii) and (xxii) combined.

	£	s.	d.
Cooking and heating, 11 070 units at $1\frac{1}{4}$d.	57	13	$1\frac{1}{2}$
Lighting, £7 × 1·7 fixed, plus 1 800 units at $1\frac{1}{2}$d. . . .	23	3	0
Power: Units per quarter per E.H.P. are below limit at which (xxii) applies, hence charge is according to tariff (xiii), as in previous example	92	10	0
Average price per unit, 1·43*d*.	173	6	$1\frac{1}{2}$

276. Bibliography (*see* explanatory note, § 58).

Costs, Tariffs, etc., in British and Colonial Supply Stations.

Tables of Costs and Records (Supplement to the *Electrical Times*).
Electrician Electrical Trades Directory (Benn Bros.).
Manual of Electrical Undertakings. E. Garcke (Electrical Press).
Central Station Tables (Rentell).

I.E.E. Papers.

Small Electricity Supply Undertakings, P. A. Spalding. Vol. 48, p. 2[illegible]7.

Residence Tariffs, A. H. Seabrook. Vol. 49, p. 376.

Tariffs for Electrical Energy, with particular reference to Domestic Tariffs, W. W. Lackie. Vol. 49, p. 147.

Electricity Supply of Large Cities, G. Klingenberg. Vol. 52, p. 133.

Electric Supply; Present Conditions and the Hopkinson Principle, J. R. Blaikie. Vol. 59, p. 701.

Multi-Part Tariffs for Domestic Electricity Supply, J. W. Beauchamp. Vol. 59, p. 714.

And others too numerous to mention.

Miscellaneous.

Every supply authority issues its own schedule of tariffs and supply conditions; a representative selection of these (§ 275) may be studied with advantage. They have not the force of law, as in the case of the 'Regulations' of the Electricity Commissioners; in fact it is doubtful if they are always *intra vires*.

The Annual Report of the Electricity Commissioners may be expected always to review developments in tariffs and tariff policy.

PART III.—TRANSMISSION AND CONTROL.

CHAPTER 13.

INSULATED WIRES AND CABLES.

277. **Applications of Insulated Conductors.**—Insulated conductors are used for the wiring of practically all installations indoors and outdoors. Outdoors permanent (fixed) circuits can sometimes be provided more cheaply by bare conductors than by insulated cables, but, against the cost of insulation on the latter, there must be set the cost of the poles (or brackets) and insulators required by bare conductors; also, the obstruction caused by, and the risk of accidental contact with, bare wires in works' yards and similar situations. The last-named consideration applies in yet greater degree to interior installations, and almost the only uses for bare circuits indoors are as contact wires for travelling cranes and in carrying low-voltage current for electro-chemical and electro-metallurgical purposes. Insulated cables are also used for the transmission and distribution of electricity (generally underground) wherever accommodation cannot conveniently be provided for overhead lines, or where the use of the latter would be dangerous. In the early days of electricity supply, bare distributing cables were stretched on insulators in underground conduits and a few examples of this practice may still be in existence. The same principle is used extensively in the contact rails of the conduit-tramway system (Chapter 34) but there a bare conductor is essential, in order that continuous sliding contact may be made, and the conductor itself is rigid. The relatively small copper conductors required for general distribution service need closely-spaced supports in order that the conductor may not sag into contact with the conduit; for this reason and because the system cannot easily be insulated for high pressures, insulated cables are now standard.

Bare conductors are used mainly for overhead transmission

and their characteristics and constants are therefore dealt with in Chapter 14, where, also, there are discussed certain features of high voltage cables associated with power transmission over considerable distances. Special features of colliery cables are discussed in Chapter 32.

278. Low and Medium Voltage Wires and Cables.—For installation work insulated stranded copper wires should be used. The size of the copper conductor will depend primarily on the current to be carried. If, however, the length of any particular circuit is considerable, the loss of volts due to the resistance of the copper must also be taken into account (§§ 24, 286); otherwise the lamps and apparatus may not get their correct pressure even when the wire is carrying much below its maximum safe current. It is generally specified (following the I.E.E. wiring rules) that the loss of volts in the conductors, from the entrance of the supply up to any apparatus, when the whole installation is switched on, shall not exceed 2 °/ₒ of the supply pressure plus a fixed allowance of 1 V, *i.e.* say, $3\frac{1}{4}$ V on 110 V circuits and $5\frac{1}{2}$ V on 220 V circuits. As will be seen when dealing with branch circuits (Chapter 22) these are generally so laid out that a single size of wire can be safely used throughout for lighting or fans—not for heating—but the cables leading to the distribution boards require to be worked out carefully. On power and heating circuits the drop in volts is not of so much importance, and the size of conductors is then determined by their permissible rise of temperature; this, with rubber insulated cables, should be limited to 20° F. whatever the purpose for which current is used, while with paper or fibre insulated cables a rise of 50° F. is allowable (§ 291).

279. British Standard Sizes of Insulated Annealed Copper Conductors.—Formerly there were thirty-two standard sizes of conductors from 0·001 to 1 sq. in. nominal area; with three exceptions these were stranded wires and in most cases the size of the individual wires was quoted in S.W.G. numbers (*see* Table 39). In order to simplify and cheapen manufacture, the number of standard sizes was reduced to twenty-five (between the same limits of nominal area) by the B.E.S.A. Specification No. 7, 1922. At the same time, the sizes of the individual wires were specified in inches throughout. However, S.W.G. numbers are still much used and there is, of course, a vast amount of conductors of the

TABLE 39.—*Old and New British Standard Sizes for Insulated Annealed Copper Conductors.*

Old Standard.		New Standard.	
Number and S.W.G. and / or Dia. in Ins. of Individual Wires.	Nominal Area in Sq. In.	**Nominal Area in Sq. In.**	**Number and Dia. in Ins. of Individual Wires.**
1 / 20 (·036″)	0·001 0	0·001 0	1 / ·036
—	—	0·001 5	1 / ·044
1 / 18 (·048″)	0·001 8	—	—
3 / 22 (·028″)	0·001 8	—	—
—	—	0·002 0	3 / ·029
7 / 25 (·020″)	0·002 2	—	—
3 / 20 (·036″)	0·003 0	0·003 0	3 / ·036
7 / 23 (·024″)	0·003 1	—	—
1 / 16 (·064″)	0·003 2	0·003 0	1 / ·064
7 / 22 (·028″)	0·004 2	—	—
—	—	0·004 5	7 / ·029
7 / 21½ (·030″)	0·004 9	—	—
7 / 20 (·036″)	0·007 0	0·007 0	7 / ·036
7 / 19 (·040″)	0·008 6	—	—
—	—	0·010 0	7 / ·044
7 / 18 (·048″)	0·012 5	—	—
—	—	0·014 5	7 / ·052
7 / 17 (·056″)	0·017 0	—	—
7 / 16 (·064″)	0·022 1	0·022 5	7 / ·064
—	—	0·030 0	19 / ·044
19 / 18 (·048″)	0·033 8	—	—
7 / 14 (·080″)	0·034 6	—	—
—	—	0·040 0	19 / ·052
19 / 17 (·056″)	0·045 9	—	—
19 / 16 (·064″)	0·060 0	0·060 0	19 / ·064
19 / 15 (·072″)	0·075 0	0·075 0	19 / ·072
19 / 14 (·080″)	0·093 7	—	—
—	—	0·100 0	19 / ·083
37 / 16 (·064″)	0·116 8	0·120 0	37 / ·064
19 / 13 (·092″)	0·125 0	—	—
37 / 15 (·072″)	0·150 0	0·150 0	37 / ·072
37 / 14 (·080″)	0·182 4	—	—
37 / ·083″	0·200 0	0·200 0	37 / ·083
37 / ·092″	0·250 0	0·250 0	37 / ·093
37 / ·104″	0·300 0	0·300 0	37 / ·103
61 / ·092″	0·400 0	0·400 0	61 / ·093
61 / ·104″	0·500 0	0·500 0	61 / ·103
61 / ·112″	0·600 0	0·600 0	91 / ·093
91 / ·101″	0·750 0	0·750 0	91 / ·103
127 / ·101″	1·000 0	1·000 0	127 / ·103

TABLE 40. *Insulated Wires and*

The figures in this Table apply to single cables run in pairs and touching one not exceed 80° F. (26·7° C.).* The figures in columns 3, 3a, 4, and 4a have been currents corresponding, in the case of rubber insulated cables, to a rise in that of the surrounding air. The lengths in circuit given in columns 3a and 4a assumption that the temperature of the cable will be 100° F. in the case of rubber

No. of Wires and Dia. of Each Wire.	Nominal Sectional Area of Conductors.	Rubber Insulated Cables.		Paper or Fibre Insulated Cables.		Minimum Insulation Resistance of 1 Mile in Megohms at 60° F.		
		Maximum Current.	[illegible]	Maximum Current.	[illegible]	Vulcanised Rubber. Up to 250 V.	Vulcanised Rubber. Up to 660 V.	Paper or Fibre (Class B).
1.	2.	3.* †	3a.	4.* †	4a.	5.	6.	7.
Ins.	Sq. In.	Amperes	Ft.	Amperes	Ft.	Megohms.	Megohms.	Megohms.
1 / ·036"	0·001 0	4·1	31	4·1	31	2 000	5 000	[illegible]
1 / ·044"	0·001 5	6·1	31	6·1	31	2 000	5 000	
3 / ·029"	0·002 0	7·8	31	7·8	31	1 250	4 500	
3 / ·036"	0·003 0	12·0	31	12·0	31	1 250	4 500	
1 / ·064"	0·003 0	12·9	31	12·9	31	2 000	5 000	
7 / ·029"	0·004 5	16·2	31	16·2	31	1 250	4 500	
7 / ·036"	0·007 0	24	31	24·2	31	900	4 000	
7 / ·044"	0·010 0	31	39	43	31	900	4 000	
7 / ·052"	0·014 5	37	46	57	31	900	4 000	
7 / ·064"	0·022 5	46	56	75	33	900	3 500	140
19 / ·044"‡	0·030 0	—	—	—	—	—	—	—
19 / ·052"	0·040 0	64	72	104	42	750	3 000	120
19 / ·064"	0·060 0	83	84	135	49	750	3 000	110
19 / ·072"	0·075 0	97	91	157	53	600	3 000	110
19 / ·083"	0·100 0	118	99	191	58	600	3 000	100
37 / ·064"	0·120 0	130	105	210	64	600	3 000	90
37 / ·072"	0·150 0	152	114	246	66	600	3 000	90
37 / ·083"	0·200 0	184	125	296	73	600	2 500	90
37 / ·093"	0·250 0	214	135	343	79	600	2 500	90
37 / ·103"	0·300 0	240	147	385	87	600	2 500	80
61 / ·093"	0·400 0	288	165	464	97	600	2 500	80
61 / ·103"	0·500 0	332	175	540	102	600	2 500	80
91 / ·093"	0·600 0	384	184	624	107	600	2 500	80
91 / ·103"	0·750 0	461	188	738	111	600	2 500	70
127 / ·103"	1·000 0	595	204	932	123	600	2 500	70

* The figures in columns 3 and 4 may be multiplied by the following constants

† In lighting circuits where the determining factor is the drop in volts (Rule

‡ This conductor was added to the British standards in the 1922 edition of at the time of going to press.

Cables, I.E.E. (Vide Rules, § 280).

another, and refer to situations where the maximum temperature of the air does supplied by the National Physical Laboratory, those in columns 3 and 4 are the temperature of 20° F., and, in the case of paper insulated cables of 50° F. above when working at the currents given in columns 3 and 4 are calculated on the insulation and 130° F. in the case of paper insulation.

Conductor Resistance in Standard Ohms per 1 000 Yds. at 60° F.	Conductor Weight in Lbs. per 1 000 Yds. (B.E.S.A. Standard).	Minimum Radial Thickness.				No. of Wires and Dia. of Each Wire.
		Vulcanised Rubber.		Paper or Fibre. (Class B.) Up to 660 V.	Lead Sheath. On Paper or Jute Cables.	
		Up to 250 V.	Up to 660 V.			
8.	8*a*.	9.	10.	11.	12.	13.
Ohms.	Lbs.	Ins.	Ins.	Ins.	Ins.	Ins.
23·59	11·77	0·034	0·055	—	—	1 / ·036″
15·79	17·58	0·034	0·055	—	—	1 / ·044″
12·36	23·37	0·036	0·056	—	—	3 / ·029″
8·019	36·02	0·038	0·057	—	—	3 / ·036″
7·463	37·20	0·036	0·057	—	—	1 / ·064″
5·281	54·39	0·039	0·058	—	—	7 / ·029″
3·427	83·81	0·041	0·059	0·080	0·060	7 / ·036″
2·294	125·2	0·043	0·060	0·080	0·060	7 / ·044″
1·643	174·9	0·046	0·061	0·080	0·060	7 / ·052″
1·084	264·9	0·049	0·062	0·080	0·060	7 / ·064″
0·846 8	340·4	—	—	—	—	19 / ·044″
0·606 3	475·5	0·056	0·063	0·080	0·060	19 / ·052″
0·400 2	720·3	0·062	0·065	0·080	0·070	19 / ·064″
0·316 2	911·6	0·066	0·066	0·080	0·070	19 / ·072″
0·238 0	1 211	0·072	0·072	0·080	0·070	19 / ·083″
0·205 6	1 403	0·075	0·075	0·080	0·070	37 / ·064″
0·162 5	1 776	0·080	0·080	0·080	0·070	37 / ·072″
0·122 3	2 360	0·088	0·088	0·080	0·070	37 / ·083″
0·097 38	2 963	0·095	0·095	0·090	0·080	37 / ·093″
0·079 39	3 635	0·102	0·102	0·090	0·080	37 / ·103″
0·059 08	4 886	0·114	0·114	0·100	0·090	61 / ·093″
0·048 16	5 994	0·121	0·121	0·100	0·090	61 / ·103″
0·039 61	7 290	0·125	0·125	0·100	0·100	91 / ·093″
0·032 29	8 942	0·131	0·131	0·110	0·100	91 / ·103″
0·023 14	12 481	0·141	0·141	0·110	0·110	127 / ·103″

for the classes of cable shown: Concentric, 0·93 ; 3-core, 0·88 ; 4-core, 0·82.
40), the maximum currents may be less than those shown in columns 3 and 4.
the B.E.S.A. Specification No. 7 ; the data for the I.E.E. table are not available

old standard sizes still in service; the comparison between the old and new standards in Table 39 (p. 391) will therefore be found useful.

280. I.E.E. Rules regarding Insulated Wires and Cables.—The following extracts from the I.E.E. wiring rules explain the basis on which Table 40 (reprinted from the same rules) is drawn up. Col. 8*a* has been added from B.E.S.A. Specification No. 7, 1922. The data on which the cols. 8 and 8*a* are based are given in § 62, and, as noted there, a variation of 2 % is allowable from the standard resistances and weights. The use of the single unstranded wires should generally be avoided, although allowed by the I.E.E. rules. The most generally useful sizes for branch wiring are 3 / ·029 and 3 / ·036 (old 3 / 22 and 3 / 20); and for sub-mains 7 / ·029, 7 / ·036, 7 / ·052, 7 / ·064, 19 / ·052, and 19 / ·064 (old 7 / 22, 7 / 20, 7 / 18, 7 / 16, 19 / 18, and 19 / 16). In Table 40 the maximum current permissible is based upon the temperature rises specified by wiring rule 43 below (*see also* § 291). The following are the actual rules of the I.E.E., Nos. 39-52, relating to conductors as entered in the table on previous page:—

CONDUCTORS—SIZE AND CONDUCTIVITY.

39. *Size.*—Except for wiring fittings, the cross-sectional area (Table, col. 2) of any copper conductor must not be less than that of a No. 18 S.W.G. The cross-sectional area of fittings wires must not be less than that of a No. 20 S.W.G.

40. Subject to Rules 39 and 43 being complied with, the minimum size of the conductors within a building will be determined as follows:—

(*a*) *Lighting Circuits.*—For lighting circuits, by the permissible drop in volts, which under ordinary conditions must not exceed 2 %, *plus* a constant allowance of 1 V (Table, cols. 3*a* and 4*a*).

(*b*) *Power and Heating Circuits.*—For power and heating circuits, by the rise in temperature, which must not exceed 20° F. (11·1° C.) (Table, cols. 3 and 4).

41. *Conductivity: Sulphur.*—Insulated copper conductors must be of annealed copper, and they must have a conductivity not less than that laid down by the Engineering Standards Committee (Rule 57 § *62*), and the copper must be protected by tinning or other effective method (Rule 56, § *285*) from contact with the insulating material if such contains sulphur.

42. *Stranding.*—All insulated copper conductors having a greater cross-sectional area than that of a No. 16 S.W.G. wire must be stranded.

43. *Table* (*vide Table* 40).—The maximum permissible currents for the various sizes of conductors up to 1 sq. in. in cross-sectional area are shown in cols. 3 and 4 of the Table, which allow for a rise of temperature of 20° F. (11·1° C.) for rubber insulated cables (Rule 45), and of 50° F. (27·8° C.) for paper or fibre insulated cables. Below 0·005 sq. in. cross-sectional area for rubber insulated cables and 0·017 sq. in. for paper insulated cables the table is based on a current density of

4 000 A per sq. in.* Cols. 3*a* and 4*a* show the corresponding lengths in yards of single conductor in circuit for each volt of fall of potential when the maximum continuous current is in use.

CONDUCTORS—INSULATION.

44. *Temperature.*— Conductors, except as provided in Rules 75 and 76, *Chapter 23*, must be specially insulated with material which does not rapidly deteriorate at the highest temperature to which it will be subjected; for instance, rubber must not be allowed to exceed 130° F. (54·4° C.), and paper or fibre 176° F. (80° C.).

45. The insulating material on any conductor other than a flexible must be throughout either—

Class A. Vulcanised Rubber.—A non-hygroscopic dielectric,† such as vulcanised rubber of the best quality, which only needs mechanical protection (Rules 63-66, § *283, and Chapter 23.* Or

Class B. Paper and Fibre.—A hygroscopic dielectric,† such as impregnated paper or fibre, which must be encased in a waterproof sheath, generally of soft metal, such as lead, drawn closely over the dielectric.

46. *Thickness.*—The radial thickness of vulcanised rubber must not be less than that given in cols. 9 and 10 of the Table. The radial thickness of dielectrics of Class B must not be less than that given in col. 11, and the radial thickness of the lead sheath not less than that given in col. 12. The dielectric must not soften sufficiently, under working conditions, to allow displacement of the conductor from the centre.

47. *Pressure Test.*—The dielectric must be such that when the insulated conductor has been immersed in water for 24 hrs., it will, while still immersed, withstand a pressure test of 1 000 V for ½ hr. in the case of 250 V cables (Rule 16, § *4*); and one of 2 500 V for ½ hr. in the case of 650 V cables (Rule 17). The testing pressures must be alternating pressures at a frequency of 50 to 100 supplied from an alternator capable of giving an output of not less than 5 kW.

48. *Insulation Resistance Test.*—The minimum insulation resistance, when corrected to a temperature of 60° F. (15·6° C.), must be that given in cols. 5 and 6 of the Table for vulcanised rubber, and that given in col. 7 for Class B, the test being made after 1 minute's electrification at not less than 500 V, and after the insulated conductor has been immersed in water for 24 hrs. immediately preceding the test, and while still immersed.

49. *Twin and Multiple Conductors.*—Each insulated member of a twin or multiple conductor must have the insulation resistance given in the Table for single conductors of the same size.

50. *Taping and Braiding.*—Conductors insulated as in Class A must be taped and braided if drawn into conduits, and at least braided if laid in casing.

51. *Colours for Conductors.*—Where colours are used to distinguish the conductors, the following are recommended :—

---

* *Author's Note.*—It will be seen that the permitted current density in paper cables is about 4 000 A per sq. in. from 0· 001-0·01 sq. in.; 2 000 A per sq. in. about 0·1 sq. in.; and 1 000 A per sq. in. for 0·5-1·0 sq. in. In rubber cables from 0·01-1 sq. in. the current density may be about two-thirds the above values. These easily memorised figures are useful for rough estimates.

† *Dielectric* does not include braiding or taping.

Continuous current: +, red; −, black; Neutral, yellow or white.
Alternating current: (*a*) Phase, red; (*b*) Phase, yellow or white; (*c*) Phase, blue; Neutral, green.

52. *Concentric Conductors.*—Concentric conductors must in all respects conform to the requirements laid down for single conductors; the insulation resistance of the dielectric separating the two conductors must be that given in the Table for single conductors having the same diameter as the inner conductor. The insulation resistance of the dielectric on the external conductor, where insulated, must be that given in the Table for single conductors having the same diameter as the outside diameter of the external conductor.

281. Grade of Cables.—Electrical wires and cables are sold as being of a certain 'grade' of insulation resistance (§ 71). The three grades most generally used are known as 300, 600, and 2 500 megohm grades; these figures represent the minimum insulation resistance per mile for the largest size of cables in each grade (§ 4). Thus, in the 600 megohm grade cables, from about 19 / ·072 ins. (19 / 15 S.W.G.) upwards will actually have this resistance per mile; smaller cables of this grade, insulated to the same specification, will have higher actual insulation resistance, up to 1 200 or even 2 000 megohms per mile in the smallest sizes (*vide* cols. 5 and 6 of Table 40). This is due to the fact that the reduction in wire diameter, and hence in its leakage surface in contact with the insulation, more than compensates for the reduced radial thickness of insulation.

For example, a 61 / ·103 ins. cable has 0·121 in. radial thickness of vulcanised rubber (up to 250 V), and the conductor is 0·936 in. in diameter. Similar data for a 7 / ·064 ins. cable are 0·049 in. radial thickness of insulation and 0·192 in. conductor diameter; and for a 1 / ·064 in. conductor, 0·036 in. radial thickness and 0·064 in. diameter. If the 61 / ·103 ins. cable be of 600 megohm grade, its actual insulation resistance will be 600 megohms per mile; and if the smaller cables be of the same grade, their actual insulation resistance may be taken (approximately) as varying directly with the radial thickness of insulation and inversely with the conductor diameter, the latter being proportional to the surface of wire in contact with the insulation per unit length of cable. This basis of calculation is not strictly accurate,* but it is near enough for estimating purposes and to illustrate the fundamental distinction between actual insulation resistance and grade. On this basis, the actual insulation resistance of 7 / ·064 ins. cable of 600 megohm grade = 600 × (0·049 / 0·121) × (0·936 / 0·192) = 1 190 megohms per mile. Similarly, that of 1 / ·064 in. cable = 600 × (0·036 / 0·121) × (0·936 / 0·064) = 2 600 megohms per mile. The actual values given in Table 40 are respectively 900 and 2 000 megohms per mile.

From Rule 48 (§ 280) it will be seen that the I.E.E. standards

* For a theoretically accurate treatment of the problem *see Electric Cables and Networks*, by A. Russell (Constable), 2nd edition, p. 62.

for vulcanised rubber cables are 600 megohm grade up to 250 V and 2 500 megohm grade up to 650 V. The insulation resistance of paper or fibre cables is much lower, and is from 70-110 megohms per mile in sizes of cable for which vulcanised rubber cables have actually their 'grade' values of insulation resistance. So far as India is concerned—and probably this applies to the tropics generally—the use of the 300 megohm grade is not recommended; the 2 500 megohm grade has been largely used, and is still used in certain provinces, but it has proved unsatisfactory in many places, and the intermediate grade is on the whole by far the most serviceable. Cables are generally put up in coils of 110 yds. or $\frac{1}{16}$ mile, and the actual insulation resistance of a single coil should, therefore, be 16 times as high as that given in the table for a mile.

Two qualities of cable are manufactured in Great Britain, known as 'Association' and 'Non-Association' cables, respectively, according to whether the dielectric complies with the specification of the 'Cable Makers' Association' or not. The higher quality is recommended as preferable; each coil should have the 'C.M.A.' label attached. It may be added, however, that certain manufacturers who do not belong to the C.M.A. make cables to the specification of that body, and that some of the special 'tropical' brands of cable have been found more serviceable abroad than 'C.M.A.'; in some instances the same manufacturers supply both qualities and recommend the non-Association 'tropical' quality as preferable to the other.

As regards the rubber insulation of cables, it is sometimes specified that it shall stand dry heat at 270° F. for 2 hrs., and moist heat at 320° F. for 4 hrs. without its qualities or elasticity being impaired.

282. Purpose and Testing of Tinning on Copper.—Rubber insulated wires are always tinned, and it is not always realised that the function of tinning is no less to protect the rubber from the catalytic oxidising effect of copper than to protect the latter from sulphur in the rubber. Beaver's test for the efficiency of the tinning is the following: Clean with alcohol or ether and immerse for 1 min. in dilute hydrochloric acid sp. gr. 1·088, rinse with water, immerse in sodium sulphide solution sp. gr. 1·142 for 30 secs.; repeat the cycle till the wire visibly blackens; this should take at least four cycles.

For the efficient use of the test the sodium sulphide solution should be prepared by dissolving 25 gms. of pure mono-sulphide of sodium in 100 cu. cms. of water, adding an excess of sulphur and boiling for about 1 hr. with occasional stirring. The solution should then be cooled, filtered, and diluted to the required specific gravity of 1·142. As there is a slight tendency for this solution to decompose on prolonged standing, depositing sulphur, it should be freshly prepared. The preparation of the hydrochloric acid is simply a matter of dilution to the required specific gravity (C. J. Beaver, *Jour. I.E.E.*, Vol 53, p. 70).

Good tinning should have a slightly golden tint. Blackening means that the tinning is imperfect, but silver-white appearance is also to be regarded with suspicion. Imperfectly vulcanised rubber adheres to the metal.

Silvery brightness of the tin coating after vulcanisation casts suspicion on the quality of the rubber. It has nothing to do with the purity of the tin or its application to the wire. A low-grade foreign wire may often be detected by this feature alone. During vulcanisation of the (inferior) rubber, acid products—due to the method of preparing the 'pure' rubber layer or to reactions in organic loading constituents, other than rubber—may be formed which slightly 'pickle' the tin and prevent formation of tin sulphides. A high-grade rubber compound takes longer than an inferior compound to vulcanise, and due to this and to the absence of 'pickling' there is formed the slightly golden film of tin sulphide which is regarded by cable inspectors as probable indication of excellence (Beaver, *loc. cit.*).

283. **Class of Cables.**—The term 'class' in regard to cables refers to the protecting covering over the dielectric, which may be of any of the grades mentioned in the preceding paragraph. Pure rubber strip wound in two or three layers with staggered joints and covered with tape and braiding forms a type of insulation which is only suitable up to 100 V or so, and is obviously not moisture-proof. Vulcanised india-rubber (V.I.R.) cables are standard for ordinary work, and it is usually sufficient if the cable is externally 'taped and braided.' It is frequently remarked that, when there is any difference in durability, black-finished rubber cables always last longer than red-finished ones. The difference is attributed by Beaver to the presence of resin in the ozokerite compound with which the braiding is saturated. The natural colour of ozokerite is black. The operation of dyeing it red is facilitated by presence of resin, but resinous matter is absorbed with avidity by rubber, to the great detriment of the latter. The presence of resin is not essential, but its exclusion involves extra cost. Unless it is certain that attention has been paid to this point, there is sound justification for preferring black-finished cable.

Vulcanised india-rubber cables are often lead-covered, and copper is sometimes used as protective covering (Chapter 23). Where extra mechanical strength is required, 'armoured' cable is used, the protection consisting of galvanised iron wire or tape, single or multiple. Round-wire armouring is generally used on small sizes of cable and also where the armouring has to carry weight, as in cables suspended vertically in pit shafts. Metal tape probably affords better mechanical protection than is given by round wires; wires of special inter-locking section are sometimes used and these combine flexibility with a high degree of mechanical protection. Armouring may be used in combination with braiding (within or without the armouring, or both), or over a lead sheath. Impregnated tape between lead and steel reduces the risk of cutting or deforming the lead by the armour and prevents electrolytic action between the two metals. Impregnated hemp or jute may be used to protect the armouring. Wherever paper or other hygroscopic dielectric is used, lead sheathing is essential (besides impregnation of the paper, § 287), and great care must be taken to ensure that the ends of the cable are sealed and the joints moisture-proof. Paper-insulated cables are seldom used for house wiring or for small sizes of branch wiring; their use for high-tension work is practically standard (§§ 287, 288). Vulcanised bitumen is a waterproof insulating material, often considered treacherous in its mechanical properties, but greatly improved during recent years. It is largely used in mining work (Chapter 32), and to a limited extent for general distribution mains. It may be lead sheathed and armoured or it may be used unsheathed or as a sheathing for paper-insulated cables. Special forms of protection have been devised for a variety of purposes. Thus there are fireproof cables; special trailing cables for serving portable underground machines, where rough usage is inevitable; acid-proof cables, and so on. The use of asbestos as a fire-resisting covering for cables is not without risk, since the asbestos may serve as a wick for oil in case of switchboard fires or explosions.

'Cab-tyre sheathed' cables consist of single or multiple core V.I.R. cables with a substantial sheathing of rubber similar to that used for cab tyres, and chosen for its mechanical properties and chemical inertness. This sheathing will stand a great deal of rough usage and all conditions due to steam, oil, acid, alkali, etc., which are likely to be encountered in practice. Besides its

use in industrial service of all kinds, this class of cable is suitable for general wiring work. It is useful in making connections to lift cars and in wiring to cookers in kitchens. It can be run in plaster unprotected, and in general wiring it eliminates condensation, leakage, and corrosion troubles, particularly if used in conjunction with special terminal and connecting boxes in which the wire is taken down through an outer vessel and up into an inner 'bell,' the mouth of which is sealed by insulating oil in the outer vessel when the whole is assembled.

I.E.E. Rule 65 relates to uncased wiring with tough rubber compound protection, and specifies that—

65. Insulated conductors protected by an outer reinforcing covering of tough rubber compound not less than 50 mils thick and capable of resisting abrasion, acids, oils, and alkalis, may be used without conduits or wood casing provided that—(*a*) The resistance of the covering to fire is equal or superior to that of vulcanised rubber; (*b*) the covering encloses the insulated conductors as a whole or each insulated conductor separately; (*c*) the conductors comply with the insulation requirements of Rules 47 and 48, § *280*.

British standard dimensions for armouring, bedding, braiding, serving, cab-tyre sheathing, etc., on insulated copper conductors for power and light service are given in B.E.S.A. Specification, No. 7, 1922.

284. Flexible Wires.—For hanging pendant lamps, and for connecting up portable apparatus to wall plugs, etc., the ordinary wires shown in Table 40 are too stiff; and special flexible wires ('flexibles') are used, consisting of many strands of very fine copper wire. The Cable Makers' Association standards are 0·007 6 in. and 0·012 in. dia. (corresponding to Nos. 36 and 30 S.W.G.) for the strands; strands 0·004 8 in. dia. (No. 40 S.W.G.) have often been used in non-Association flexibles, but such fine wires are apt to be brittle, particularly if tinned. Old and new standard sizes of flexible cords are shown in Table 41. For similar particulars concerning flexible cables, ranging from 140 / ·010 in.-792 / ·029 in. (0·01-0·5 sq. in. nominal area), *see* B.E.S.A. Specification No. 7, 1922.

The thickness of insulation is greater in C.M.A. than in Non-Association flexibles, and if tinning be used instead of cotton lapping the larger diameter of strands (as compared with Non-Association flexibles) compensates for the effect of tinning in making fine wires somewhat brittle. I.E.E. rules as to the insulation of flexibles are given in the next paragraph. Over the dielectric

TABLE 41.—*Standard Sizes and Approximate Current-Carrying Capacity of Flexible Cords.*

Old Standard.				New Standard.			B.E.S.A. Standard Resistance per 1 000 yds. at 60° F. Ohms.	Approximate Carrying Capacity (Table 40). Amps.	Approximate Overall Dia.* In.	Approximate Equivalent Solid Wire, S.W.G.
Number of Wires of Size.			Nominal Conductor Area Sq. In.	**Number of Wires of Dia.**		**Nominal Conductor Area Sq. In.**				
40 S.W.G. (0·004 8″).	38 S.W.G. (0·006″).	36 S.W.G. (0·007 6″).		**0·007 6″.**	**0·0 2″.**					
34	22	14	0·000 6	14	7	0·0006	39·7	2·5	·24-·28	22
56	36	22	0·001 0	23	11	0·0010	24·2	4·1	·27-·30	20
100	64	40	0·001 8	40	16	0·0017	13·9	7·0	·29-·32	18
178	114	71	0·003 2	70	28	0·0030	7·94	12·9	·33-·36	16
278	178	111	0·005 0	110	44	0·0048	5·05	19·0	·37-·40	14
—	—	—	—	162	65	0·0070	3·43	24·0	·41-·42	13

there is generally a covering of either cotton or silk, and two or three separate wires are then twisted together to form a twin or triple flexible. Where subject to rough use the two wires are padded to a circular shape and then covered by an outside protective layer of braiding; this class is known as 'workshop flexible.'

It is sound policy to assume a low current-carrying capacity for flexibles (particularly in the smaller sizes), because individual strands often break at many points, particularly in leads supplying vacuum cleaners, flat irons, and other portable apparatus. The resulting local reduction in effective copper section increases the current density at the point affected.

Useful information on the mechanical testing of flexibles for wearing quality, etc., is to be found in Report No. 32529 of the Electrical Testing Laboratories to the National Electric Light Association (U.S.A.); *see also Electricity*, Vol. 34, p. 772.

285. **I.E.E. Rules as to Flexibles.**—The wiring rules of the I.E.E. (Nos. 53-56) lay down the following requirements as to flexibles:—

* Depending on type of protective covering.

53. *Size.*—Flexibles must be made up so that the total cross-sectional area is not less than equivalent to No. 22 S.W.G., and they must be composed of wires twisted together on a short lay, no wire being smaller than a No. 36 S.W.G.

54. *Dielectric and Tests.*—The insulating material used as the dielectric must be pure rubber equal to washed para rubber or vulcanised rubber of the best quality. The pure rubber must be laid on in two layers, care being taken that the edges of each layer overlap, and the radial thickness of the dielectric must not be less than 20 mils. Each coil of pure rubber flexible must be tested in air for 15 minutes with a pressure of 1 500 V alternating between the conductors at a frequency of 50-100.

55. *Vulcanised Rubber.*—Vulcanised rubber flexible must be insulated with one layer of pure rubber and two layers of vulcanised rubber; the minimum insulation resistance and radial thickness of the dielectric must be those specified in the Table (§ *280*) for 250 V or 650 V cable having similar cross-sectional area of conductor. In the case of flexibles having a conductor cross-sectional area less than 0· 000 9 sq. in., the radial thickness must not be less than 33 mils for low pressures and not less than 62 mils for medium pressures. The pressure tests and insulation tests must be applied before braiding, and as specified in Rules 47 and 48, § *280*, with the exception that the pressure tests may be applied for 15 minutes only.

56. *Sulphur.*—Insulating material containing sulphur must not be in direct contact with copper wires (Rule 41, § *280*).

286. Drop of Volts in Cables.—In col. 3*a* of Table 40 (§ 280) are given the approximate lengths of each size of wire in which, with the current in the preceding column flowing, there will be a drop of 1 V. If the current is halved the length for the same drop of pressure will be doubled, and so on, in inverse proportion.

For example, using 3 / ·029 ins. wire, if the current carried is the maximum allowable, *viz.* 7·8 A, the drop is 1 V in about 31 ft. Therefore, if the pressure of the supply in question is 220 V, and we arrange for 4 V drop in the branch wires (out of the 5½ V allowable, § 278), we are limited to 124 ft. of wire, *i.e.* 62 ft. run of lead and the same of return.

Generally the length of wire and the current are known and it is required to find the size of wire which must be used. Thus, the pressure being 110 or 220 V, we may generally allow up to 2 or 4 V drop respectively in the branch wiring; now by Ohm's Law the total resistance of the conductor will be E / I, E being the *drop* in volts allowed; then if we know the total length (lead plus return) and the resistance of that length (by the above calculation) the resistance per 1 000 yards can be found at once by simple proportion, and from this the nearest size of wire can be selected from the wire table (col. 8), as in examples (Table A on opposite page).

Care must be taken to see that the cable selected on the basis of voltage drop is not too small for the current it has to carry; this may be ascertained by reference to col. 3 of Table 40. Also, if the size comes out smaller than 3 / ·029 ins. (3 / 22 S.W.G.), that wire is the smallest which should ordinarily be used. Of two

TABLE A.—*Examples in Selecting Size of Conductor, on the Basis of Assumed Voltage Drop.*

Drop Allowed E.	Current I.	$R = E / I$.	Length Lead and Return.	Proportional Resistance per 1 000 Yds.	Nearest Size from Col. 8 of Table 40.
V.	Amperes.	Ohms.	Yds.	Ohms.	S.W.G.
2	5	0·4	40	10	3 / 21
4	5	0·8	60	13·4	3 / 22
2	7	0·28	50	5·7	7 / 22
2	7	0·28	80	3·5	7 / 20
2	13	0·15	30	5	7 / 22 or 3 / 18

sizes, in cases of doubt, it is better to use the larger, especially if the current is near the maximum allowable by the Table or if the air temperature is liable to exceed 80° F. In the case of mains and sub-mains, where extensions may cause an increase of current, it is also best to be liberal in the size used.

287. Insulating Materials for High-Pressure Cables.—General information concerning insulating materials is to be found in Chapter 2. The notes here given relate to the characteristics of various insulating materials as affecting the use of the latter in high-voltage cables (*see also* §§ 281, 283 for low-voltage cables, and § 288 for extra high-pressure cables). The inductance and capacity of cables are discussed in §§ 310, 311.

Air under pressure (§ 78) has been used experimentally as dielectric for high-voltage 'cables;' with a $\frac{1}{4}$ in. conductor inside a 4-in. iron tube, and air at 120 lbs. per sq. in., it is possible to transmit energy at 60 000 V (J. S. Highfield, *El. Rev.*, Vol. 91, p. 919).

Rubber is too costly for use as insulating material on high-pressure cables ; it has a high insulation resistance, but has lower break-down pressure than paper, and both the insulation resistance and dielectric strength of rubber depend greatly on its composition and degree of vulcanisation. The proportion of pure rubber in the mixture is generally from 30-60 °/₀. Rubber insulation is liable to attack by ozone and nitric acid formed from the atmosphere in the neighbourhood of e.h.t. conductors ; a sheathing of bitumen between rubber and conductor eliminates this risk. The lower specific inductive capacity of paper as compared with rubber is an advantage in cable construction.

The general properties of *vulcanised bitumen* include a tendency to break short at low temperatures, particularly under shock, and to soften and permit decentralisation of conductors when heated in service. However, manufacture of these cables has improved greatly during recent years. Two- and three-core bitumen cables are generally found more reliable than single-core cables, and A.C. cables give less trouble than C.C. cables of this type. Vulcanised bitumen is immune from attack by acids, but alkalis cause a certain amount of surface attack. From an extensive investigation, C. J. Beaver concludes that the softening of bitumen by saponification is attributable to leakage current, moisture (in so far as the latter is required to render braiding conducting), and heat, the effect increasing with the time these conditions endure. Saponification troubles occur only on negative cables, since it is only there that alkali is produced electrolytically. The incorporation of 5-10 °/₀ of high-grade vulcanised rubber in vulcanised bitumen is said to give a material free from any softening trouble, even under severe conditions of practice, and superior to either ingredient alone. The principal use of bitumen cables is as distributors in mining and other industrial service; a bitumen sheathed cable with bitumen "wormings" between the component conductors, which are themselves insulated with bitumen is practically moisture-proof. The bitumen should be forced into the interstices between the strands of each conductor to prevent "creeping" of moisture from a defective point.

Paper insulation is employed in most cables for pressures of 3 000 V or higher, owing to its good mechanical and electrical properties. Suitable paper stands heating in service better than rubber; also it is cheaper than rubber and has a very high breakdown pressure (about 200 kV (R.M.S.) per cm., as a commercial maximum, with 120 to 150 kV as the basis for guarantees), though its insulation resistance is low, say 70-100 megohms per mile in large and 150-300 megohms per mile in small paper cables. Unusually high insulation resistance in paper-insulated cables does not necessarily indicate over-heating of the latter in manufacture and is not a reasonable basis for rejection, though it is sometimes laid down as such in specifications. In this country, pure manilla paper is considered best for insulating purposes; on the Continent, paper containing a proportion of wood pulp is often used, on the ground that it absorbs impregnating oil more freely. Probably

the cheapness of the impure paper is a major consideration. Paper-insulated cables may be impregnated (under heat and vacuum) after the paper is applied, or the paper strip may be impregnated before being wound on the cable. In the latter case a more viscous impregnant may be used, the heating period for drying out the cable may be reduced, and no difficulty is found in excluding air bubbles. The impregnating compound should not set stiff or hard but should be oily in nature so that the paper is not torn when the cable is bent. Break-down by ionisation results if voids are caused by the paper absorbing filling material from the interstices of the strand, or by the impregnant not flowing to fill up bends. Paper itself is very hygroscopic, and no impregnation renders it waterproof to the extent required for insulating purposes; hence it is most important to protect all joints and ends during laying, and to keep them perfectly sealed when in service.

Varnished cambric (*Empire cloth*) is used, particularly in America, as insulation for cables which may be exposed to oil or acid as in the case of connecting-cables in power houses, switch-boards, accumulator rooms, etc. In these applications the cable can be used with a simple braiding and the ends need not be sealed. Though much less hygroscopic than paper, varnished cambric must be lead sheathed if it is to be used underground. For underground service paper insulated cables are generally to be preferred.

British Standard thicknesses of dielectric, sheathing, and armouring for various types and classes of cable are specified fully in B.E.S.A. Report, No. 7.

288. Extra High-pressure Cables.—The object of using very high pressures for transmission purposes is to reduce the weight of metal required to conduct the power in question. However, this idea must not be carried too far, particularly in insulated cables. The electrostatic strain on the insulation surrounding a charged conductor increases with the pressure to which the latter is charged, and also increases with the curvature of the conductor, *i.e.* is greater for a small wire than for a larger wire charged to the same pressure. The minimum permissible conductor radius in a high-tension cable is $r = (V / S)$ cms., where V = R.M.S. volts p.d. between conductor and sheathing, and S = maximum safe dielectric stress in R.M.S. volts per cm. (*see also* § 72). This

assumes that the conductor is circular in section. If it be stranded, the sharp curvature of the outer-strand conductors themselves will intensify the electrostatic stress, but this may be overcome by pressing a lead sheathing on to the stranded conductor so as to give it a smooth cylindrical surface. If the minimum radius r, determined by consideration of electrostatic stress, be greater than the radius dictated by consideration of electrical conductivity and mechanical strength, the weight and cost of the conductor may be kept down by adopting a tubular section of external radius r. A rigid tube of metal would be of very limited applicability, but flexibility may be maintained by using a ring of small conductors laid on to a lead-tube core, to keep them in position, and sheathed with lead to obtain a smooth circular periphery. By using a paper tube as mandrel for the outer ring of conductors, and placing an ordinary stranded conductor inside the paper tube, the 'split conductor' needed by the Merz-Price protective gear (§ 359) can be obtained without increasing the overall conductor diameter (as compared with the previously mentioned lead-tube core construction).

There is no special difficulty in insulating cables for pressures up to 20 000 V between cores, and 3-core, 33 000 V cable is now a standard commercial product. If required, 3-core, 44 000 V or 66 000 V cable could, it is believed, be supplied under satisfactory guarantees. For underground transmission at higher pressures between phases it would probably be cheaper and safer to use single-core cables (*see also* § 319). The Gennevilliers (Paris) system uses considerable lengths of 33 000 V single-core cable, with 60 000 V between phases.

A typical British 3-core cable for operation at 33 000 V between phases has three stranded conductors, each of 0·2 sq. in. section and covered with ¼ in. layer of paper; round the three cores is another ¼ in. layer of paper, outside which comes the lead sheathing, a jute bedding, double armouring, and the outer serving of jute. There is thus ½ in. of paper between cores and between each core of the lead sheath. The cable is about 4 ins. diameter overall and weighs 72 lbs. per yard.

289. Graded Insulation and Intersheaths for E.H.T. Cables.—*Graded Insulation.*—Where a charged cylindrical conductor is surrounded by a uniform thickness of a homogeneous insulating material, the electrostatic stress on the latter is much more intense on the inner layers, adjacent to conductor, than on the outer layers. In other words, the 'potential gradient' is not

uniform, and the inner layers of insulation may be broken down or deteriorated by overstrain (*see*, however, § 72). One way of overcoming this difficulty is to use successive layers of different insulating materials having different specific inductive capacities. The complete insulation then consists of a number of concentric tubular condensers connected in series, and the distribution of pressure through the insulation is determined by the electrostatic capacity (§§ 46, 60, 79, 107 ii) of the several layers. Theoretically, the total electrostatic stress could be distributed uniformly through the whole thickness of insulation by this means, but in practice the method involves grave difficulties. In the first place, consideration of manufacturing cost limits us to, say, three or four layers of insulation, so that the resultant pressure gradient curve consists necessarily of a number of 'steps.' The chief difficulty, however, is to obtain even a few insulating materials of suitable electrical and mechanical properties, which can be used in the first place and relied upon to preserve their properties unchanged, and not to attack each other chemically in the course of twenty or thirty years. The intersheath method is more flexible and probably more reliable.

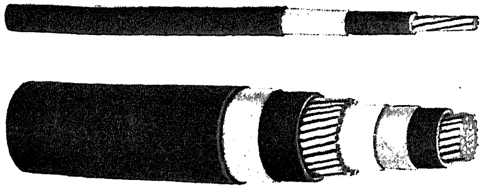
Intersheaths.—An alternative method of maintaining definite potentials at certain depths in the insulation, thus ensuring that the electrostatic stress across intervening parts shall not exceed a predetermined maximum, consists in laying on thin metallic sheathings from time to time during the application of the insulation, which is itself of the same material throughout. There are thus obtained a series of concentric electrodes in the insulation, which can be 'anchored' at any desired potential; the potential gradient in the outer layers of insulation may be higher than in the inner layers because the outer layers are cooler and therefore of higher insulation resistance (§ 71) and lower dielectric loss. The potentials of the 'intersheaths' may be fixed by condensers connected between them, or by tapping connections from transformer or generator windings at suitable points, or, in the case of high-tension C.C. on the Thury system (§ 317), by small natural or artificial leakage currents, tappings being taken from the connections of the series-connected generators. The intersheaths themselves may be of lead; they can then be applied easily with smooth interior and exterior surface, and the cable can be tested thoroughly after each intersheath is applied—which is an

important manufacturing advantage. The intersheaths may also be used for maintenance tests in service (Chapter 40); or they may be of copper wire and used for power transmission (§ 319).

As described by Beaver (*Jour. I.E.E.* Vol. 53, p. 57), a single cable designed for use in a 3-phase line, for a working pressure of 100 kV per phase and a breakdown pressure of 250 kV per phase, consists of an inner lead tube of 0·27 in. bore and 0·06 in. radial thickness, on which is a single layer of nineteen 15 S.W.G. wires sheathed by an outer lead tube of 0·05 in. radial thickness. The first layer of paper insulation is 0·545 in. in thickness, and is covered by a 0·05 in. lead intersheath. The second layer of paper is 0·565 in. thick, and the outer lead sheath is 0·16 in., bringing the overall diameter of the cable to 3·27 ins. The maximum stress in the dielectric at the working pressure is 52 kV per cm., giving a factor of safety of about 2½. By accepting a lower factor of safety, the overall diameter could be reduced yet further.

The difficulties encountered in manufacturing intersheath cables have been overcome, and sample 100 000 V cables have given satisfactory results on test. The conditions calling for grading (either by graded insulation or by intersheaths) are: (1) working pressures exceeding 60 kV; (2) maximum stresses above 60 kV per cm.; (3) where cable diameters, without grading, would exceed, say, 3 ins. For most practical purposes one intersheath will suffice. The saving possible by using graded cable is greater the higher the working pressure and the smaller the conductor to be insulated. In the present state of practice, such cables as considered above are required only for short-distance interconnecting with e.h.t. transmission lines in city areas or round about power houses, railways, etc. Should long intersheath cables come into use, their considerable capacity current (§ 311) will necessitate 'feeding' the intersheaths at intervals along the line, unless, of course, the Thury C.C. system (§ 317) is employed.

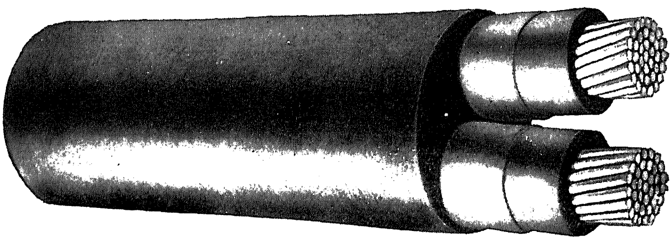
290. Cable Construction, Jointing, and Laying.—The conductors in cables are generally stranded and of circular cross-section, either of rope form (two conductors being placed side by side, or three at the apices of a triangle), or tubular, as in concentric cables. Single-core cables are easier to make, lay, and joint than 3-core cables, but the eddy current losses in the sheaths are heavier and if single-core A.C. cables be armoured the inductance becomes excessive. Probably the largest 3-core cable yet built is a 3 × 0·5 sq. in., 11 000 V cable connecting a 12 000 kVA generator to the bus bars in the Neepsend station. The use



B.I. & Helsby Cables, Ltd.

RUBBER INSULATED CABLES.

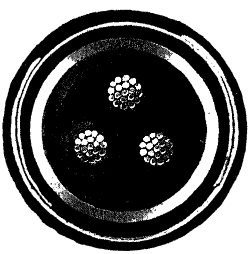
The upper illustration shows a small single-core cable and the lower a concentric cable. The tinned copper conductor is first covered with a layer of pure rubber. Outside this there is a layer of separator rubber (usually light coloured) containing a small percentage of sulphur; and then the jacket rubber, with the full quantity of sulphur for vulcanisation. The cable is lapped with proof-tape, vulcanised, cotton-braided, and impregnated with ozokerite compound. In the concentric cable, a tape containing a large proportion of zinc oxide is placed between the outer conductor and the taping of the inner.



B.I. & Helsby Cables, Ltd.

VULCANISED BITUMEN CABLE.

The vulcanised bitumen is applied, under high pressure, to the conductor while warm. A thin separator of impregnated paper is sometimes interposed between the conductor and the bitumen.

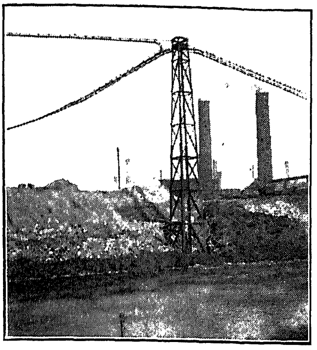


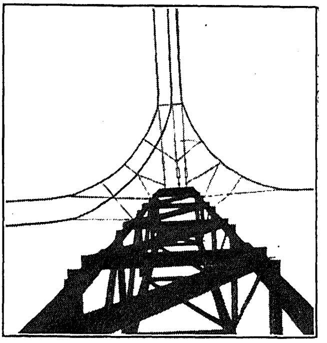
G.E.C. (London).

PAPER-INSULATED LEAD-SHEATHED CABLE.

Cross-section of three-core, 0·1 sq. in. cable to B.E.S.A. specification for 10 000 V. Insulated with impregnated paper, lead-sheathed, served with compounded jute, double steel tape armour, and compounded jute serving overall.

[*To face p.* 408.

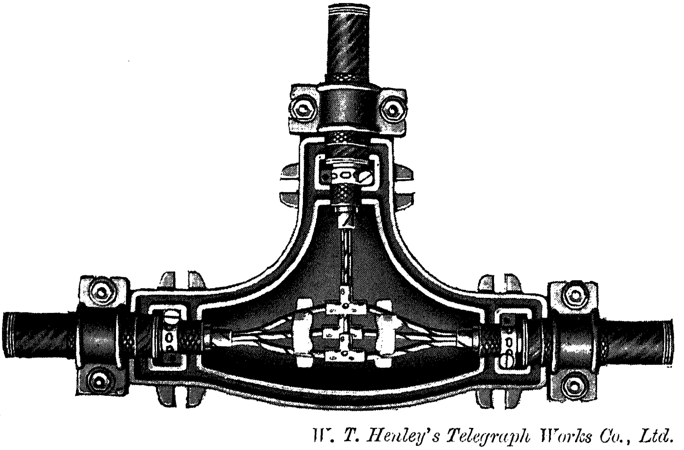




Johnson & Phillips, Ltd.

INSULATED POWER CABLES CARRIED BY OVERHEAD STEEL WIRES.

The three cables illustrated (0·04 sq. in. and 0·06 sq. in. for 2 200 V, and 7 / 15 S.W.G. for 6 600 V) are all 3-core, paper-insulated, lead-covered cables with weather-proof serving. They are suspended from a 19 / 14 S.W.G. steel suspension wire on steel towers at about 35 yds. span; and the height of the wires above ground is about 45 ft. Fully insulated and served cables were employed because of corrosive fumes from blast furnaces near by, and because the cable passes over several roads and railways. Also, it is intended to mount steam pipes on the same towers, and it would be undesirable for men to work on these pipes below bare high-tension wires.



W. T. Henley's Telegraph Works Co., Ltd.

SOLID-TYPE BRANCH BOX FOR 3- OR 4-CORE PAPER-INSULATED, LEAD-COVERED AND ARMOURED CABLES.

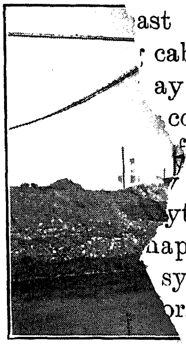
The tee-connections are made by means of tinned brass connectors with steel grub-screws and solder holes. The cores are held apart by porcelain spreaders and the box is filled with molten insulating compound through apertures provided in the cover (not shown in the figure).

[To face p. 409.

of tubular or ring-formed conductors to reduce ele
is discussed in § 289. Individual cores may be
concentric sections lightly insulated from eac
circular form (or elliptical form in 3-core cables)
to use the split-conductor protective system
'pilot' wires are then unnecessary. The elli
ductor saves space as compared with circul
unduly increasing electrostatic strain. Up to 1 00
shaped cores effect important saving in size an
cables, particularly when the copper sectio
In high-tension cables the additional insul
enhanced electrostatic stress at the corn
balances the saving otherwise to be deriv
form of the sectors. The economic po
conductors are reviewed in §§ 308, 331
ductor is about 29 °/。 larger in diameter
of equal conductivity, the extra insu
quired is a serious consideration.

Insulating materials and their 'grading
287, 289. A point of some importance in laying out
bution schemes is the possibility of saving money by
cables which can subsequently be operated at higher
than at first, the change being made when demanded by
in the load supplied. The question whether an existing c
safely be run at higher pressure than was originally conten
depends upon the factor of safety then allowed, and up
history of the cable in service, *i.e.* the average and max
current densities at which it has been worked and the pr
surges to which it has been exposed. As explained in § 298
cables must withstand higher maximum pressures (apart f
surges) than C.C. cables working at the same effective press
Also the maximum dielectric stress (§ 289) must be kept dow
in A.C. cables to avoid serious heating by dielectric losses (§ 312).

Single or double armouring may be used, according to local conditions, if the cable is to be laid directly in the ground; and it is then a sound precaution to place a row of tiles or the like over the cable before filling in. Round wires are generally used for armouring, fewer being required, though they are heavier than segmental wires. Tape armouring tends to pull open under tension (as in pit-shaft cables). The conductivity of the armouring



ast 50 % of that of the largest conductor en-
cables (Chapter 32); in single-armoured cables,
ay have 25 % of the conductivity of the largest
copper sheath within but separated from the
frequently employed. To resist corrosion by
be galvanised and covered by an impregnated
ytic corrosion of cables by stray earth-current
hapter 35.
system of laying cables, the latter are placed on
ors in a cast-iron or stoneware trough, which is
bitumen or compound and closed by a cover-
m unarmoured cables are generally employed.

INSULATED PO

The three cables
S.W.G. for 6 600 V) a
proof serving. They
steel towers at about
45 ft. Fully insulat
from blast furnaces near by, and
railways. Also, it is intended
be undesirable for

ems are not satisfactory in the tropics, but
pp and; the facility with which fresh cables
arm nes withdrawn for repair, is an important
heavy traffic on roads is apt to injure
re discu e; in such cases flexibility should be
the cable 'direct' or by laying it on the
mexible wooden troughing.

laid directly in the ground or on the solid system have
ilities for cooling than cables which are drawn into
he drawing-in process necessarily involves some risk of
the cable. The cost of trenching and tunnelling when
ables may often be greatly reduced by using the Mangnall-
thrust borer.' This is an hydraulic machine which drives
of any desired diameter (up to 12 ins. as a maximum under
rable circumstances) on a predetermined alignment through
rth between two access pits which may be, say, 40 ft. apart.
soil is displaced (*not* removed) and the hole is thus left with
nsolidated surface which will allow a cable to be drawn through
thout undue resistance. If desired, pipes can be left in the
hole as it is bored (*El. Rev.*, Vol. 90, p. 545).

Joints in cables may be made in junction boxes or, permanently, in the run of the cable itself. In the latter case the general aim is to make the joint electrically as similar as possible to the cable itself. Insulating material, such as impregnated paper strip or rubber tape, may be built on to jointed conductors, or the conductors may be held apart by porcelain or other separators, a lead casing being then wiped on to the lead sheathing at each side of the joint and filled with molten insulating compound.

The latter should be kept warm for a time, and there should be a reserve of hot compound in the extended top or funnel of the casing to make up for contraction as the mass cools. Sharp edges or points of solder on the joint, air-bubbles or films, and inclusion or ingress of moisture are particularly to be guarded against, especially in h.t. cables.

291. **Heating of Cables.**—The heating of various types of cables under various service conditions is important because it determines the maximum current which may safely be carried by the cable. The current-carrying capacities of rubber insulated and paper or fibre-insulated cables as specified in Table 40, § 280, apply to single cables run in pairs and touching one another and refer to situations where the maximum temperature of the air does not exceed 80° F.; also, they correspond to a rise in temperature (above that of the surrounding air) of 20° F. in the case of rubber-insulated cables and 50° F. in the case of paper-insulated cables. To determine the maximum current permissible in multi-core cables (for the same temperatures), the values given in Table 40 must be multiplied by 0·93 for concentric cables; 0·88 for 3-core cables; and 0·82 for 4-core cables.

The Henley Manual gives tables of current-carrying capacities of insulated cables (for pressures up to 6 000 V) based approximately on the following data:—

(*a*) *For situations where the air temperature does not exceed 80° F.*: The safe carrying capacities for *two single cables* laid together are: For rubber cables erected in air, wood casing, exposed or buried conduit; and for paper, lead-sheathed cables in ducts underground; the same as shown in Table 40 (§ 280) for rubber and paper cables respectively. For bitumen insulated cables in ducts underground, about 0·9 times the values for rubber-insulated cables (assuming that the bitumen cable is not allowed to reach a total temperature higher than 110° F.)

The safe current for *one single cable* or for *one multi-core cable* is obtained approximately by multiplying the value for two single cables by a factor as follows:—

For one single cable multiply by 1·1.
For one concentric (or twin) cable multiply by 0·93.
For one 3-core cable multiply by 0·88.
For one 4-core (or twin concentric) cable multiply by 0·82.

If *several cables are laid together*, multiply the safe current for one cable by 0·9 for two cables; by 0·85 for three cables; and by 0·8 for four cables.

If the *cable is installed otherwise than stated above*, multiply the value so far obtained for the safe current by a factor as follows:—

Method of Installation.	Rubber Cable.	Paper, Lead-sheathed Cable or Bitumen Cable.
Cleated to wall	1·0	0·9
In underground duct	1·1	1·0
Solid system	1·2	1·1
Direct in dry soil	1·3	1·2
„ „ wet „	1·4	1·3
Under water	1·5	1·5

(*b*) *For situations where the air temperature exceeds 80° F.* In addition to the correction factors given above, which must be applied successively in so far as they are applicable, the safe current value now obtained must be multiplied by a factor to allow for the higher initial temperature of the air, as follows :—

Initial Air Temperature.	Rubber Cables.	Paper Cables.	Bitumen Cables.
° F.			
90	0·87	0·93	0·82
100	0·71	0·85	0·58
110	0·50	0·76	—
120	—	0·65	—
130	—	0·54	—
140	—	0·38	—

Example.—What is the safe current for four, 3-core paper cables laid solid in a situation where the initial air temperature is 110° F.? Each core is a 7 / ·064 conductor.

From Table 40, the safe current for two single paper cables of this size is 75 A. Multiplying this value successively by 0·88 because 3-core cables are concerned; by 0·8 because four cables are laid together; by 1·1 because the cables are laid solid; and by 0·76 because the initial temperature is 110° F., we have: Safe current $= 75 \times 0{\cdot}88 \times 0{\cdot}8 \times 1{\cdot}1 \times 0{\cdot}76 = 44$ A (approx.).

It should be noted that the air temperature in the shade is no guide to the temperature 2 or 3 ft. below ground where the surface is exposed to the full sun and may reach 160° F. or higher temperature.

The heating in a buried cable on load varies with the method of laying, with the thermal properties of the insulating materials, and with the current density in the cable (*see also I.E.E. Report*, § 293). If the temperature rise be excessive the insulating material deteriorates and the cores in vulcanised bitumen cables may be decentralised. The total temperature should not exceed 120° F. for rubber cables; 150° F. for paper cables; and 110° F. for bitumen cables. In practice, trouble due to overheating generally takes the form of pulling-out at joints, and of broken or crumpled sheathing, due to the forces of expansion and

contraction; direct injury by the actual temperature attained is seldom experienced. In emergency, the carrying capacity of cables laid in ducts can be increased by forcing cool air through the ducts by blowers situated at alternate manholes, the warm air escaping at the intermediate manholes. Cables supplying cyclic loads (*i.e.* loads which demand current for relatively short periods followed by periods of little or no demand) may carry considerably higher current than would be permissible continuously; the actual safe current can only be determined by plotting the heating and cooling curves of the cable from tabulated experimental data, or by direct measurement of the steady temperature reached after a prolonged series of duty cycles.

[At the time of going to press a report on the heating of buried cables is in preparation by the B.E.R.A. and will be published in the *Journal* of the I.E.E.]

292. Submarine Cables.—There are a number of cases in which electric power cables (as distinct from telegraph and telephone cables) are laid in sea-water, across bays, channels, estuaries, etc. The following notes are instructive:—

Two cables were laid (in 1915) a distance of 13 000 ft. across the Golden Gate (San Francisco) to deliver 18 000 H.P. at 11 000 V. Each cable has three copper cores (of 350 000 circ. mil * area at the shore ends and 250 000 circ. mil * for the deep-water sections), insulated by rubber and varnished cambric, and enclosed in a 5/32-in. lead sheath. Two layers of jute form a cushion for the steel armouring, which in turn is covered by jute and a layer of sand and asphaltum. The overall diameters of the shore end and deep-water sections of the cable are $4\frac{1}{2}$ ins. and 4 ins., the weights being 22 and 19 lbs. per ft. respectively. Since the tide runs at 6 knots and the water is over 200 ft. deep (from which depth the cable could not safely be hoisted for repair), each power cable is carried by a $1\frac{3}{8}$-in. stranded steel messenger cable. The two cables are bound together by a continuous winding of two galvanised wires, soldered every 12 ins. (to prevent unwrapping should the wire break), and wound in a number of turns at one point every 20 ft. The messenger cable relieves the cable and joints from all tension. There are eleven splices in each completed cable. The safe carrying capacity of the cables is 350 A

---

* In the U.S.A. the standard unit in which to express the sectional area of wires is the *circular mil* (circ. mil or C.M.). The term circular mil denotes the area of a circle 1 mil or 0·001 in. in diameter; hence 1 circ. mil = 0·785 4 sq. mil = $7{\cdot}854 \times 10^{-7}$ sq. in. = $5{\cdot}067 \times 10^{-4}$ sq. mm. The sectional area of a round wire in circ. mils is numerically equal to the square of its diameter expressed in mils (*i.e.* in thousandths of an inch). Conversely, the diameter of the wire in mils = $\sqrt{}$(Area in circ. mils). Thus 350 000 circ. mils = 0·274 9 sq. in., and is equivalent to a solid round wire of $\sqrt{350\,000}$, *i.e.* 590 mils or 0·59 in. diameter. Similarly, 250 000 circ. mils = 0·196 4 sq. in., and is equivalent to a round wire of 0·5 in. diameter.

or 400 A in emergency. The specification required a test pressure of 30 000 V, 60 cycles between cores for 30 mins.; the actual break-down pressure is 100 000 V between cores (*see also El. Rev.*, 78, 443).

More recently a 25 000 V cable has been laid $3\frac{1}{2}$ mls. under the sea, at a maximum depth of 125 ft., between Palsjö (Sweden) and Marienlyst (Denmark). This cable supplies about 5 000 kW, 3-phase A.C., and uses impregnated paper insulation, a fact which involved very great care in making joints at sea whilst laying the cable. The twin copper cores (0·019 sq. in. each) are insulated for 35 000 V, and the cable is lead-sheathed, and armoured by special Z-shaped wires. The overall diameter is 3·6 ins., and the weight 19 lbs. per ft. run. Iron coupling boxes 5 ft. in length transmit strain in the armouring across the lead-sheathed joints, of which there are eight. A steel cable is laid alongside to protect the power cable from damage by anchors.

As will be gathered from these particulars, any waterproof cable of suitable mechanical strength can be used under water, the chief problem being to provide for laying and recovering it without mechanical injury. The stiffness of adequately armoured cables makes them difficult to handle; for this reason and because of the high capacity of the cable (§ 311) the length of submarine power cables is limited to a few miles. The cable may be carried on the cable-laying ship by a drum capable of rotation about a vertical axis, or it may be coiled in figure-of-eight formation on deck. The external covering of compounded jute is mainly useful in preventing damage during laying. It is difficult to make splices whilst laying the cable, and splices are always a source of electrical and mechanical weakness; they may be avoided, in cables of 2 mls. or so in length, by using cable insulated with rubber compound and with no lead sheathing.

The construction of a cable of this type laid, in 1922, between N. Brothers and Rikers Islands, East River (N.Y.) is: Two No. 0 A.W.G. stranded conductors, each insulated with $\frac{12}{64}$ in. of 30 % rubber compound and covered by one rubber filled tape. The insulated conductors are twisted with paraffined jute fillers, and over this is a rubber filled tape and two layers of asphalted jute. The latter serves as bedding for a layer of No. 6 A.W.G. galvanised steel wire armour (drawn through asphaltum compound before application); outside this is a layer of No. 4 A.W.G. galvanised steel wire wound in the opposite direction. The complete cable is 2·92 ins. outside diameter and weighs 31·8 lbs. per yard.

293. **Bibliography** (*see* explanatory note, § 58).

REGULATIONS, ETC.

Board of Trade Regulations (Electric Lighting Acts, 1882 and 1888); Publication 2 C (P) (Stationery Office).

Electricity Commissioners' Regulations (Under Sec. 4 of Electric Lighting Act, 1888); Publication El. C. 12 (Stationery Office).

Electricity Commissioners' Regulations as to Extra High Pressure (Electricity (Supply) Acts, 1882-1919); Publication El. C. 13 (Stationery Office).

H.O. Electricity Regulations for Factories and Workshops (Stationery Office).

Mines and Quarries Form No. 11 (Coal Mines Act, 1911). Regulations as to installation and use of Electricity (Stationery Office).

I.E.E. Wiring Rules (Spon).

B.E.S.A. Report No. 7. Insulated Annealed Copper Conductors for Electric Power and Light.

The Indian Electricity Rules, 1922; "The Law Relating to Electrical Energy in India," by J. W. Meares (Thacker Spink, Calcutta).

BOOKS.

Electric Cables, their Construction and Cost. D. Coyle and F. J. O. Howe (Spon).

Electric Cables. F. W. Main (Pitman).

Theory of Electric Cables and Networks. A. Russell (Constable).

Electric Mains and Distributing Systems. J. R. Dick and F. Fernie (Benn Bros.).

I.E.E. PAPERS.

Insulation of Cables. M. O'Gorman. Vol. 30, p. 608.

Dielectric Strength of Insulating Materials and Grading of Cables. A. Russell. Vol. 40, p. 6.

Cables. C. J. Beaver. Vol. 53, p. 57.

Research on the Heating of Buried Cables. Vol. 59, p. 181.

The Rating of Cables for Intermittent or Fluctuating Loads. S. W. Melsom and H. C. Booth. Vol. 61, p. 363.

The Use of Single-Core Sheathed Cables for A. C. W. Cramp and N. S. Calderwood. Vol. 61, p. 477.

Permissible Loading of British Standard Paper-Insulated Cables. (B.E.R.A. Report.) Presented to I.E.E., March, 1923.

CHAPTER 14.

TRANSMISSION OF POWER: OVERHEAD AND UNDERGROUND.

294. D.C. and A.C. Calculations.—In this chapter examples are first worked out by approximate formulæ which give, near enough for practical purposes, the results required; then the more ordinary, but less simple, methods of working are explained. Transmission of power by continuous current is practically confined to feeders, except where the Thury high-pressure, constant current, series system is employed (§ 317). The calculation for the size of the conductors for D.C. working is quite straightforward (*see* § 296), there being then no question of power factor or self-induction. With alternating current, on the other hand, complications are introduced by the fact that the pressure and current are seldom in phase; causes of low-power factor and typical values for the P.F. at each end of transmission lines are given in §§ 156, 157.

It must always be remembered that, although laboratory tests are capable of exact calculation, the size of conductors in transmission lines must be one that is manufactured, and, even so, a variation of 2 °/₀ is permissible in the resistance and weight. Again, the exact length of the conductors (which in hilly country is by no means the scaled length on a map), their spacing and temperature, and the actual maximum load to be carried, are all approximations when the calculations are made. So also is the power factor of the load, which is speculative until consumers' requirements are definitely known. On this account some of the calculations following are really carried unnecessarily far, although only slide-rule results. If numerical examples are not worked out fairly closely, they may not be clear.

295. General Formulæ for Copper.—The approximate sectional area of the conductor, in square inches, required for any

transmission line, may be found by the following formula, *viz.* :—

$$\text{Area} = \frac{kW \times D \times n}{V^2 \times L \times P.F.} \text{ where}$$

kW = kilowatts delivered at *end* of line ;
D = route yards in length of line ; *not* lead and return ;
V = voltage at point of use ;
L = percentage loss of V (as 5 or 10, not as a decimal) ;
n = a constant as follows :—
(i) D.C. or 1-phase, 2-wire system . . . . $n = 4{\cdot}9$, say 5
(ii) D.C. or 1-phase, 3-wire system ; V measured across outers ; for outer conductors . . . . $n = 4{\cdot}9$, say 5

Note.—The neutral is generally taken half the size of the outers (*see* Chapter 20).

(iii) D.C. or 1-phase, 3-wire system ; V measured between outer and neutral ; for outer conductors . . $n = 1{\cdot}25$
(iv) 3-phase mesh or star system ; V measured between any 2-phase wires . . . . $n = 2{\cdot}5$
(v) 3-phase star system ; V measured between outer and neutral . . . . $n = 0{\cdot}833$

$P.F.$ = power factor of the load *at the receiving end* (§ 157).

Some engineers work out their lines from the generator end, assuming the power required there and the percentage loss of the power and pressure of the generator ; in the case of small powers this can be done, but in a complicated scheme it is obviously preferable to work out the power required at the point of utilisation, and to decide on the pressure at the lamps and motors, and then to work backwards to the plant. Where transformers are involved the latter part of § 313 shows the advantage of this method. Having found the cross-sectional area of the conductor, a reference to the table of cables (§ 280) or solid wires (§ 307), as the case may be, will show which standard size is nearest to the required size, and this should be taken. Then the weight of the conductors in lb. per yd. will be 11·56 times the area in sq. ins., and this, multiplied by D, the length of the line, will give the total weight of each wire. There will of course be two such wires for D.C. and single-phase 2-wire supply, and three such for 3-phase 3-wire lines.

From the cross-sectional area the resistance can be found from the tables ; the values given are for annealed copper in Table 40 (§ 280) and hard-drawn copper in Table 44 (§ 307). Alternatively the resistance of either annealed or hard-drawn wire per yard may be found from the expression in § 62, and this

multiplied by the route length, D, will give the resistance, R, of each wire. The values are in each case true at 60° F., but in ordinary calculations it is not necessary to make corrections for temperature. The loss of power in watts in each wire will then be I^2R and the *total* loss will be $2I^2R$ for D.C. or single-phase and $3I^2R$ for 3-phase circuits. The loss of pressure will be IR in each wire, in phase with the current. In applying this formula to overhead lines there is not likely to be any question of the conductor being too small to carry the current, but in the case of underground cables a reference should be made to Table 40, § 280, cols. 3 and 4, to see that the cable (according to its class) is not overloaded. The current (I amperes), corresponding to W watts delivered, is given by—

For direct currents, I = Watts delivered / V.
For single-phase, I = Watts delivered / V × P.F.
For 3-phase, I = Watts delivered / V × 1·73 × P.F.

The Electricity Commissioners' Regulations concerning the minimum strength of overhead lines are summarised in § 324. Hard-drawn copper wire has a breaking stress of from 25 tons per sq. in. in large sizes to 29 tons in the smaller sizes used for overhead lines. In practice it is seldom advisable to use a smaller wire than No. 6 S.W.G.

296. Direct Current Transmission.—In order to compare transmission by A.C. with that by D.C., an identical example may be worked out for each.

Assume that it is required to deliver 1 000 kW at a point 8 000 yds. from the generator, at a pressure V of 6 285 V at the delivery end, the loss in transmission being 5 % of the power delivered. Then the initial pressure will be 6 600 V and the power at the generator will be 1 050 kW. The current will be 1 000 × 1 000 / 6 285 (or 1 050 × 1 000 / 6 600) = 159 A, and the volts lost in the line 6 600—6 285 = 315 V, which is 5 % of 6 285 V. In D.C. practice these pressures would only be used with the Thury system (§ 317), but they have been assumed here because 6 600 V is a standard in A.C. work and it serves for comparison purposes.

A useful rule for D.C. circuits, involving fewer factors than the general formula in § 295, may be given here, *viz.*:—

$$\text{Area of conductor} = \frac{\text{Current} \times D}{20\ 000 \times \text{Lost volts in line}}.$$

This gives the area = 159 × 8 000 / 20 000 × 315 = 0·202 sq. in. The constant in the denominator should, strictly speaking, be 20 800 for annealed copper

and 20 380 for hard-drawn wire, at 60° F., but such accuracy is not necessary in commercial calculations. The preceding general formula will be found to give a similar result.

Working out the problem in the usual way, the *total* resistance of the line must be $= E / I = 315 / 159 = 1{\cdot}98\ \Omega$. As the *total* length is 16 000 yds., the resistance will be 0·000 123 5 Ω per yd. or 0·217 Ω per mile. From § 62 it then follows that the cross-sectional area for hard-drawn wire will be 0·000 024 53 / 0·000 123 5 = 0·198 sq. ins., agreeing with the result obtained above. The weight of this conductor will (in round numbers) be 0·2 × 11·56 = 2·31 lb. per yd. (§ 62), 18 500 lbs. for each wire and 37 000 lbs. for the line; say 16½ tons.

297. Single-phase A.C. Transmission by General Formula.—With the single-phase A.C. 2-wire system, the same *virtual* or R.M.S. pressure (§ 31), and unity P.F., the above calculations give practically accurate results at ordinary frequencies, neglecting the self-induction of the line and assuming (as may safely be done in ordinary cases) that the conductor is not large enough to cause a loss through skin effect (§ 38).

With lower P.F. the current in the circuit is increased, and more copper is needed to keep the loss of power the same.

Thus, assume that with the same effective delivery pressure, *viz.* 6 285 V, it is again required to deliver 1 000 kW with a loss of 5 % of the power delivered, the length of the line being unchanged, but the P.F. to be 0·9 instead of unity. Then the current will be 1 000 × 1 000 / 6 285 × 0·9 = 177 A, *i.e.* the current in the D.C. example divided by the P.F.; and the 'apparent power' delivered to the circuit will be 6 285 × 177 / 1 000 = 1 110 kVA (§ 56). The area of the conductor will be 0·221 sq. in., found either by dividing the D.C. value by the P.F. (*i.e.* 0·198 / 0·9) or by the general formula in § 295. The weight will now be 0·221 × 11·56 = 2·55 lbs. per yd. or 41 000 lbs. for the whole line, lead and return. This is 1·11 times the amount required for D.C. or for single-phase current at unity P.F. The factor 1·11 applies to any single-phase transmission at 0·9 P.F.

With a P.F. of 0·8 the calculations may be similarly worked out, and the results will be: Current 199 A; area of conductor 0·248 sq. in.; total weight 46 000 lbs. or 1·25 times the weight required for D.C. or single-phase current at unity P.F.

The actual loss in the above cases would be a little more than 5 %, owing to the self-induction of the line, but the result is near enough for all practical purposes.

298. Area and Weight of Conductor to give same Strain on Insulation.—It must be remembered that the *maximum* pressure corresponding to a virtual or R.M.S. pressure of 6 600 V is 6 600 × $\sqrt{2}$ or 9 400 V (§ 31); therefore the insulators in the case of A.C. overhead lines would have to be larger, or the insulation of the underground cable of higher quality, in an A.C. supply of the same virtual pressure as a corresponding D.C. supply.

To give the same strain on the insulation in the example of §§ 296, 297, which would actually be the fairer method of comparison, the virtual pressure with single-phase A.C. would have to be only 4 670 V at the generating end ($4\,670 \times \sqrt{2} = 6\,600$), so the current and size of conductor would be proportionately increased. The actual figures may be worked out from the formula given above, and they will show the D.C. system in its most favourable light (*see also* § 317).

On the other hand, if there is a fault in the insulation which can just be broken down by an alternating pressure of R.M.S. value E, it will generally be broken down by a D.C. pressure much lower than $E \times \sqrt{2}$, owing to the sustained stress produced by the D.C. pressure (the break-down voltage of insulation is lower with prolonged application of the pressure, § 72). This is an argument in favour of testing insulation by D.C. voltage (Chapter 40), but the latter does not subject the insulation to sustained capacity current, hence the dielectric loss (§ 312)—that due to leakage through the ohmic resistance—is lower and the heating of the dielectric is correspondingly reduced. For these conflicting reasons, the ratio between D.C. and A.C. pressure strain is not a physical constant.

299. Single-phase Overhead Lines; Induction, Reactance, Impedance.—Although the method employed in the example of § 297 is accurate enough for ordinary work, the effect of induction and of the current and pressure being out of phase may be followed up further. Assuming that overhead lines are being used, so that 'capacity' may be neglected (§ 304 *et seq.*), the apparent resistance or 'impedance' of conductors carrying alternating currents is made up of two components, *viz.* ohmic resistance, R, which is an absolute function of the material and temperature of the conductor; and reactance, S, which depends on the working conditions. These components may be considered as vectors at right angles, and the total impedance may be found graphically by completing the right-angled triangle (*see* Fig. 10 in § 44). Expressed algebraically:—

$$\begin{aligned}\text{Impedance} &= \sqrt{(\text{resistance}^2 + \text{reactance}^2)}\\ &= \sqrt{\{R^2 + (2\pi n)^2 \times (L\,/\,1\,000)^2\}},\end{aligned}$$

where n is the frequency in complete periods per second and L is the self-induction in millihenries (mH).

In the example in § 297, the pressure at the receiving end is 6 285 V and the energy component of the drop in the line will by hypothesis be 5 % of this or 315 V. (This is not the actual drop, as will be seen presently, for the reactance

causes a wattless or induction drop as well.) This equals IR (§ 295), and the current I (with a P.F. of 0·9) is 177 A. Therefore $R = 315 / 177 = 1·77\ \Omega$ for the whole 16 000 yds. (Note here that the power lost $= I^2R = 177^2 \times 1·77$ or 56 kW.) This resistance is equivalent to 0· 000 111 Ω per yd., giving a cross-sectional area of 0· 000 024 53 / 0· 000 111 or 0· 221 sq. in. as before (§ 297). The diameter of such a conductor, of solid copper, would be 0·53 in. In practice this would be an inconvenient size to handle and difficult to obtain, and two parallel wires each of half the equivalent cross-section would be used; but for the purpose of the example this may be waived.

Of the three factors shown under the square root sign in the above expression for impedance, the first, R, is calculated as shown in the preceding example. The product of the other two factors is the (reactance)^2, and of these $(2\pi n)^2$ at the standard frequency of 50 cycles is 98 800, or, in round numbers, 100 000. The self-induction of the line, L, must be found from the formula * :—

$$\text{Millihenries per mile} = 0·080\,5 + 0·741 \log [(d - r) / r],$$

where d = distance between centres of conductors, in ins.; and r = radius of conductor, in ins. In the case of overhead lines $(d - r)$ may be taken as d, since r is relatively small.

In the example considered, the diameter of the wire is 0·53 in., so the radius is 0·265 in., and the distance between conductors may here be taken as 12 ins. In practice the spacing would be at least 24 ins. if not 30 ins. (*see* § 327).

Then $L = 0·080\,5 + 0·741 \log (12 / 0·265) = 0·080\,5 + (0·741 \times 1·657) = 1·306$ mH per ml. or 11·9 mH for 16 000 yds. From this value of L, we have that $(L / 1\,000)^2 = (11·9 / 1\,000)^2 = 0·000\,141$. This gives the reactance,† S as $\sqrt{(98\,800 \times 0·000\,141)} = 3·72\ \Omega$, and the impedance $= \sqrt{(1·77^2 + 3·72^2)} = 4·12\ \Omega$. The energy and induction components of the voltage may now be tabulated as follows, bearing in mind that with a power factor ($\cos \phi$) of 0·9, the wattless or induction factor (§ 157) will be $\sqrt{(1 - 0·9^2)}$ or $0·436 = \sin \phi$. Both these factors are used in Table 42, and this will make their significance clear.

It will be noticed that if the impedance drop of 730 V is added to the delivery pressure 6 285 V the result is 7 015 V, whereas the actual generator pressure is only 6 860 V; this is due to the change of phase caused by self-induction in the line, as the graphical construction in § 300 will demonstrate. Ordinarily the discrepancy may be neglected, at least in preliminary estimates. The P.F. at the generator end of the line is lower than at the receiving end, owing to this self-induction. The power put into the line is seen from Table 42 to be 1 056 kW, and this equals

* An alternative form is : mH per mile = $0·160\,9\ \{0·5 + 4·605 \log [(d-r) / r]\}$.

† Or ohmic value of self-induction, which = 2π × periods × henries. The E.M.F. of self-induction = reactance × current.

TABLE 42.—*Voltage Components and Power in Single-Phase Overhead Line.*

	Voltage.		Power.
	Energy Component.	Induction Component.	
At delivery end—			
Energy component 0·9 of 6 285 V	5 650	—	Power = 5 650 × 177 = 1 000 kW as presumed.
Induction component 0·436 of 6 285 V	—	2 740	
In line—			
Resistance loss IR = 177 × 1·77 V	315	—	Line loss of power = 315 × 177 = 56 kW.
Reactance loss IS = 177 × 3·72 V	—	660	
Total . .	5 965	3 400	Power generated 5 965 × 177 = 1 056 kW.

Impedance drop = $\sqrt{(315^2 + 660^2)}$ = 730 V.
Generator pressure = $\sqrt{(5\ 965^2 + 3\ 400^2)}$ = 6 860 V.

$I \times E \times$ P.F. or 177 × 6 860 × P.F. Therefore the P.F. of the whole circuit is 0·87, not 0·9, when the line is taken into account. The ratio between 6 860 and 7 015 V, *viz.* 0·97, gives the P.F. of the line alone. Assuming the power to be given by a single generator with an efficiency of 93 %, the power required to drive it would be (1 056 / 0·746) × (100 / 93) = 1 520 B.H.P. The output of the generator, however, would be expressed as 1 210 kVA, *i.e.* kW / P.F. or 1 056 / 0·87. It will be seen from § 313 that, if the pressure at the generating station is stepped up by means of transformers, both the P.F. of the line and the kVA output of the generator would be affected; the former being lowered, and the latter raised.

300. Graphical Construction for Single-phase Lines; Power Factor of Line.—In order to ascertain the conditions in the same line graphically the following construction (Fig. 52) may be followed; it is *not* to scale, and in working out results by this method a very large sheet of paper is required:—

Fix on any arbitrary scale for representing volts and amperes respectively. Draw vector OE to represent the voltage at the receiving end of the line, *viz.*

6 285 V in the example considered. Next draw the vector OI to represent the current in magnitude and direction, the angle ϕ between OE and OI being that for which the power factor of the load is the natural cosine; in this case the angle is $25\frac{3}{4}°$ for P.F. 0·9. For the present neglect the dotted construction. The drop of pressure, 315 V, due to the ohmic resistance of the line (*i.e.* 177 × 1·77) will be in phase with the current, and is represented by ER, drawn parallel to OI, to the same volt scale as OE. The inductive drop is at right angles to the ohmic drop, and this, calculated as above, is represented by RS drawn at right angles to ER to the same scale; its value here is 177 × 3·72 or 660 V. Then ES gives the impedance drop, 177 × 4·12 or 730 V. Finally, OS gives the voltage at the sending end of the line, 6 860 V on the same scale. As the resultant or impedance drop ES is in this case (though not always) out of phase with the receiving voltage, it is not exactly equal to the difference (6 860 − 6 285), but it may safely be taken so in ordinary work. The dotted construction in this figure is explained later (§ 305) in connection with capacity.

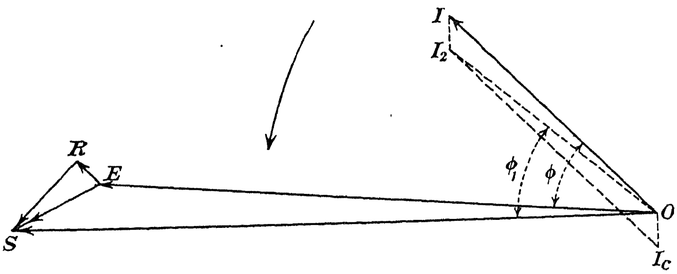


FIG. 52.—Graphical construction for single-phase line.

301. Three-phase Transmission by General Formula.—In order to facilitate comparison between the several systems, the same problem as before (§§ 296, 297) is considered, but with 3-phase supply. It is assumed that 1 000 kW is to be delivered at the end of a 3-phase, 3-wire line 8 000 yds. long, the delivery pressure being 6 285 V (virtual), and the loss in transmission being 5 °/ₒ of the power delivered.

Using the general formula in § 295, the area of each conductor in sq. ins. will be: (1 000 × 8 000 × 2·5) / 6 285 × 6 285 × 5 × P.F. = 0·101 / P.F. This gives the following values for the area and weight of the conductors with various power factors:—

	P.F. Unity.	P.F. 0·9.	P.F. 0·8.
Area of each conductor, sq. in.	0·101	0·112	0·126
Weight, lbs. per yard = area × 11·56	1·167	1·295	1·455
Total weight 24 000 yds.	28 000	31 000	35 000
Percentage of total weight for continuous current (§ 296)	75 °/ₒ	83°/ₒ	94°/ₒ
Current in each conductor, amperes	92	102	115

The current = Watts delivered / (V × $\sqrt{3}$ × P.F.) = (1 000 × 1 000) / (6 285 × 1·73 × P.F.) = 92 / P.F. As the line loss is 5 %, 1 050 kW will be put into it and the initial pressure will be (1 050 × 1 000) / ($\sqrt{3}$ × current × P.F.), or about 6 600 V in each case. For rough working this is all the information required, but in the next paragraph the matter is considered in greater detail on different lines, as in the case of single-phase transmission.

It may be noted that, as pointed out in § 298, a larger area and weight of conductor would be required to subject the insulation only to the same *maximum* pressure as in the D.C. example; this would give the D.C. system an advantage, and the Thury series system utilises it (*see* § 317).

302. Three-phase Transmission Lines; Inductance, Reactance, and Impedance.—The pressure between any two conductors in the preceding example is 6 285 V at the receiving end, and the pressure between any one wire and the neutral point will therefore be 6 285 / $\sqrt{3}$ or 3 630 V. We shall consider one of the three conductors in the first place. Each conductor will deliver one-third of the total power or 333·3 kW.

Taking as example the case where the power factor is 0·9, the *apparent* energy delivered by each branch will be 333·3 / 0·9 = 370 kVA, and the current in the branch will be 370 × 1 000 / 3 630 = 102 A, as found by another method in the preceding paragraph. Now, as the loss of power is to be 5 % of that delivered, the 'energy component' of the drop in pressure in each branch, or $I \times R$, will also be 5 % of the pressure to neutral; 5 % of 3 630 is 181 V. (The line current is in phase with this component of the total drop of pressure in the wire, so the loss of energy in each conductor will be $I \times E$ = 102 × 181 or 18·5 kW, showing the actual energy loss in the three branches to be 18·5 × 3 = 55·5 kW.) Now the ohmic resistance of each branch must be (Volts lost) / Current = 181 / 102 = 1·78 Ω for the 8 000 yds. of wire. (Note again that the loss in the branch is also equal to $I^2R = 102^2 \times 1{\cdot}78$ or 18·5 kW as before.) We then have the resistance per yd. = 1·78 / 8 000 = 0· 000 222 Ω. Area of conductor = 0· 000 024 53 / 0· 000 222 = 0· 111 sq. in. (about 3 / 0 S.W.G.). Weight = 1·29 lb. per yd. = 10 300 lbs. per branch or 30 900 lbs. for the line, *i.e.* 83 % of the amount required for D.C.

We may now ascertain the inductance and reactance of the line, with 12-in. spacing between wires as before, noting again that the actual spacing would be greater (§ 327). The diameter of the wire is 0· 376 in. or radius 0· 188 in. Self-induction = 0· 080 5 + 0· 741 log (12 / 0· 188) = 1·42 mH per ml. or 6·45 mH for 8 000 yds. (§ 299). Then $(L / 1\,000)^2 = (6{\cdot}45 / 1\,000)^2$ = 0· 000 041 6, so that—

Reactance at 50 cycles = $\sqrt{(98\,800 \times 0{\cdot}\,000\,041\,6)}$ = 2·02 Ω for each wire

$$\text{and Impedance} = \sqrt{(1{\cdot}78^2 + 2{\cdot}02^2)} = \sqrt{7{\cdot}16} = 2{\cdot}69\ \Omega.$$

Now, although there is actually but one current in the wire and one pressure between any two points, it makes matters clearer if, as in the case of single-phase, the pressure is resolved into two components at right angles, an energy component and a 'wattless' induction component. The power factor cos ϕ being 0·9, the

'induction factor' sin ϕ (§ 157) will be $\sqrt{(1 - 0{\cdot}9^2)}$ or 0·436. The various voltages, etc., in one wire will be as shown in Table 43.

TABLE 43.—*Voltage Components and Power in 3-Phase Overhead Line.*

	Voltage, between Phase Conductor and Neutral.		Power.
	Energy Component.	Induction Component.	
At delivery end—			
Energy component 0·9 of 3 630 V . . .	3 268	—	Power delivered 3 268 × 102 = 333·3 kW per branch or 1 000 kW altogether.
Induction component 0·436 of 3 630 V . . .	—	1 583	
In line—			
Resistance or energy loss $IR = 102 \times 1{\cdot}78$ V .	181	—	Power lost 181 × 102 = 18·5 kW per branch or 55·5 kW altogether.
Reactance loss 102 × 2·02 V	—	208	
Total	3 449	1 791	Power generated = 3 449 × 102 = 352 kW per branch or 1 056 kW altogether.

Impedance drop = $\sqrt{(181^2 + 208^2)}$ = 276 V; which also = (2·69 × 102) V.
Generator pressure = $\sqrt{(3\,449^2 + 1\,791^2)}$ = 3 885 V to neutral; and 3 885 × $\sqrt{3}$ = 6 730 V between phase wires.

The power required to drive a single generator to give the output required, assuming an efficiency of 93 %, would here be (1 056 / 0·746) × (100 / 93) = 1 530 B.H.P. The output of the generator would be specified as 1 200 kVA, *i.e.* 1 056 kW / 0·88, the denominator being the P.F. shown in the next paragraph.

303. **Graphical Solution for 3-phase Lines; Power Factor of Line.**—Here, again, the effect of self-induction in the line is to alter the power factor, or the phase relation of current and pressure, as shown in the graphical solution in § 300. The total power at any point in a 3-phase line is $I \times E \times \sqrt{3} \times$ P.F. and is in this case 1 056 kW at the generator end of the line; at this point, $I = 102$ A; and $E = 6\,730$ V, therefore the P.F. is 0·88 at the generator end of the line, compared with 0·9 at the load end.

Graphically, taking Fig. 52 again, *OE* will be 3 630 V and the angle *OI* will be unchanged, *viz.* $23\frac{3}{4}°$. The vector *ER* will be 181 V and *RS* will be 208 V, as shown in Table 43; *ES*, the impedance drop, will be found to be 276 V (*vide* Table 43), and *OS* will scale 3 885 V. If the impedance drop 276 V is added arithmetically to the initial pressure 3 630 V, the result is 3 906 V, not 3 885 V as obtained by vectorial addition. The difference is due to the slight alteration of phase in the line itself, owing to its self-induction, and may be neglected.

The graphical method of dealing with 3-phase problems illustrated in Fig. 53 is due to B. Welbourn, and the method of drawing and using the diagram is as follows:—

The equilateral triangle *BHJ* is drawn to scale, each side representing the pressure between phases at the loaded end. Then *AB*, *AH*, *AJ* represent the pressure to neutral (= line pressure / $\sqrt{3}$). Draw *AC*, representing to scale the

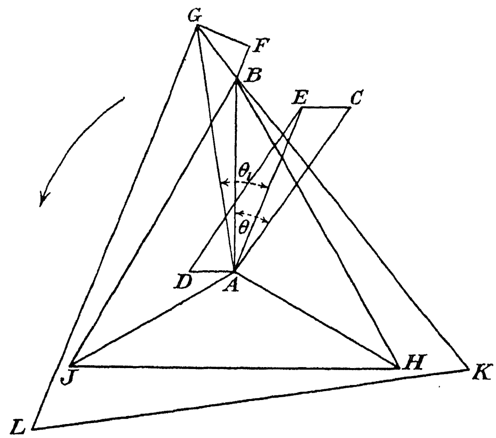


FIG. 53.—Graphical construction for three-phase line.

full-load current, lagging behind *AB* by the angle ϕ. Draw *AD* at right angles to *AB* to represent the capacity current to the same scale as *AC*. Compound *AC* and *AD* to find the resultant current, *AE*, in the line. The resistance drop in one wire is in phase with the current *AE*, and is given by $AE \times R$; its value is represented, to the same scale of volts as before, by *BF* drawn parallel to *AE*. Next draw *FG* to the same scale and at right angles to *BF*, to represent the E.M.F. of self-induction or reactance drop in one wire. Join *AG*, which gives the pressure to neutral at the generating end; this multiplied by $\sqrt{3}$ gives the pressure between phases at that point. The sides of the equilateral triangle *GLK*, completed from the centre *A* and vertex *G*, also give this. Cos ϕ_1 is the power factor at the generating end, and the kW delivered to the line is given by the product (pressure $GL \times \sqrt{3} \times$ current $EA \times \cos \phi_1$).

304. **Capacity and Capacity Reactance.**—Capacity, *i.e.* electrostatic capacity, has exactly the opposite effect to inductance, that is to say, it causes the current to *lead on* the impressed

E.M.F. instead of to *lag behind* it. Capacity in a circuit implies that the conductors or apparatus act like a condenser, which of course will not pass a continuous current. With an alternating impressed E.M.F., energy is stored up in the condenser in the form of electrostatic stress, as the E.M.F. rises, but when the wave of E.M.F. dies away this stored energy returns to the circuit, as a current leading 90° out of phase; this is called the capacity current or charging current (§ 46). If both inductance and capacity are present they tend to neutralise one another.

In the foregoing examples the existence of capacity has been ignored; in short overhead lines its effect is usually of no practical importance, but in long lines and in all underground cables it must be taken into account.

The deliberate introduction of variable capacity into transmission systems, in order to balance the induction effect of motors, etc., and improve the P.F., is discussed fully in §§ 159-62. As there explained, artificial improvement of the P.F. of a transmission system is generally a sound financial proposition, since the cost of the necessary equipment is much less than that of the generating and distributing plant otherwise rendered idle by wattless current.

Of the three factors, resistance, reactance, and 'condensance' or capacity reactance, all expressed in ohms, the two former may be considered in *series* in a line or cable, while the latter, due to capacity, is in *parallel* with the other two, as already stated in § 46. It will be seen in the examples following that, although the charging current due to capacity is often important, the effect of capacity on the total impedance of an overhead line is negligible. Capacity is expressed in microfarads (μF) or millionths of the true unit, *viz.* the farad.

305. Capacity and Charging Current of Overhead Lines, Single-phase.—The capacity of two overhead wires side by side, and relatively far from the ground, is $[0{\cdot}019\,4 / \log (D / r)]$ μF per ml., where D is the distance between the centres of the wires, in ins.; and r is the radius of each wire, in ins.; the dielectric is air, and the actual capacity varies somewhat according to atmospheric conditions.

In the single-phase line of § 299, D is 12 ins. and r is 0·265 in., so $\log (D / r) = 1{\cdot}66$. Then capacity $C = 0{\cdot}019\,4 / 1{\cdot}66$ or 0·011 7 μF per ml. run of line or 0·053 μF for the whole length of 8 000 yds.

The capacity current or charging current $I_c = 2\pi \times$ frequency $\times E \times C / 10^6$ or, at the standard frequency of 50 periods, $I_c = 0{\cdot}000\ 314\ EC$, where E is the pressure between wires at the generator end and C is in microfarads.

In the example chosen, $I_c = 0{\cdot}000\ 314 \times 6\ 860 \times 0{\cdot}053 = 0{\cdot}114$ A for the whole line or 0·025 A per ml. run. This means that in order to charge the line to full pressure, *when no power is being used*, the generator must be giving ($I \times E$) apparent watts or $6\ 860 \times 0{\cdot}114 = 785$ apparent watts. In this particular instance capacity and its consequences may be neglected, but it is worked out to show the method.

Where the charging current is of sufficient importance, as in cables, it has to be considered in connection with the main current; the main current is lagging behind the impressed E.M.F. by an angle depending on the power factor, while the charging current is leading the E.M.F. by 90°. To obtain the magnitude and phase relation of the actual or resultant current, vectorial addition is the simplest method.

This is shown in dotted lines in Fig. 52. There OS and OE are the pressures at the transmitting and receiving ends of the line respectively, and OI is the lagging energy current. The charging current OI_c is drawn to the same scale, leading, at right angles to OE. (Actually OS should be used, but OE and OS are always so nearly parallel in a scale drawing that no error will result.) Then by compounding OI and OI_c the resultant current OI_2 is found. In the subsequent construction ER should then be parallel to OI_2 instead of OI. The angle ϕ_1 will give the P.F. at the generating end.

The capacity reactance or condensance is $(1 / 2\pi n \times C)\ \Omega$, where C is expressed in farads. In this case, the capacity reactance $= 1 / (2\pi \times 50 \times 0{\cdot}053 \times 10^{-6}) = 1 / 0{\cdot}000\ 016\ 6 = 60\ 000\ \Omega$. It may also be expressed as $E / I_c = 6\ 860 / 0{\cdot}114$; or as (Apparent watts) / (Charging current)^2, *i.e.* $785 / (0{\cdot}114)^2$. The same result is obtained in each case. These relations in fact are merely an extension of Ohm's law applied to alternating capacity currents. It is obvious that this apparent resistance, in *parallel* with the impedance as determined in § 299 (*viz.* 4·12 Ω), will not affect its value appreciably.

306. Capacity and Charging Current of 3-phase Line.—In 3-phase lines the Y-capacity of the line is the same as that of one wire to the neutral point, which is $[0{\cdot}038\ 8 / \log (D / r)]\ \mu F$ per ml.

Thus, in the case already considered in § 302, D is 12 ins. and r is 0·188 in. Log $(12 / 0{\cdot}188) = 1{\cdot}81$, so the capacity is $0{\cdot}038\ 8 / 1{\cdot}81$ or $0{\cdot}021\ 4 \mu F$ per ml., *i.e.* $0{\cdot}097 \mu F$ for the whole 8 000 yds.

The capacity current or charging current in each conductor at 50 cycles will now be $[0{\cdot}000\ 314 \times (E / \surd 3) \times$ capacity in $\mu F]$, E being the line pressure and $(E / \surd 3)$ the volts to neutral at the generating end. Then $I = 0{\cdot}000\ 314 \times 6\ 730 \times 0{\cdot}097 = 0{\cdot}118$ A, which again is negligible, representing only $(0{\cdot}118 \times 3\ 885 \times 1{\cdot}73)$ or 1 380 apparent watts from the generator. The graphical solution in

§ 300 would be modified in the manner explained in the preceding paragraph, if it were necessary. The capacity reactance here is 1 / 0·000 030 4 or 6 730 / 0·118 or 790 / ($0·118^2 \times 1·73$) = 33 000 Ω, and here again it is in *parallel* with the impedance of 2·69 Ω (§ 302), and is of negligible effect.

307. **Constants of Hard-drawn Copper Wire.**—The capacity of a line varies with the size of the wires, and the charging current with the frequency of the supply; tables will be found in many books giving the values for American wire gauges and 40, 60, or 100 cycles. Table 44 gives the various constants of hard-drawn copper wire in S.W.G. and British standard units; *i.e.* the frequency in cols. 11 *et seq.* is 50 cycles.

NOTES ON TABLE 44.

Columns 1-4 require no explanation.

Column 5 is based on an ultimate strength of 25 tons per sq. in. except in the case of No. 10 wire (27½ tons).

Column 6 is dealt with in § 327, on the dip and stress of overhead wires.

Columns 7 and 8 give the resistance per yd. and mile of wire respectively based on 2 °/₀ higher resistance than annealed copper (*see* Table 40, § 280). The increased resistance to A.C., due to skin effect, is negligible at 50 cycles with all these sizes (§ 38), being much less than the permissible variation of 2 °/₀. All these columns are therefore applicable both to D.C. and A.C. transmission.

Columns 9 et seq. relate to A.C. transmission only. Col. 9 gives the nominal spacing between centres of conductors (§ 327), which of course necessarily varies considerably in a completed line; this factor enters into the calculation of all the subsequent constants, and interpolation will, if necessary, give intermediate values.

Column 10 gives the self-induction, L, of a line at each spacing, in millihenries (mH), *i.e.* (Henries / 1 000), per ml. of wire. It is based on the formula already given in § 299, neglecting the $(-r)$ in the last factor, *viz.*,

$$L = [0·080\,5 + 0·741 \log (D / r)] \text{ mH per ml.}$$

Therefore in calculating out a single-phase line either the value of L must be multiplied by the total length of wire (lead and return), as in the example in § 299, or by 2 to give the inductance of 1 ml. run of the whole line. In 3-phase calculations (*vide* example in § 302) a single wire is taken with respect to the neutral point, and the value of L in the table must be multiplied by the *route length* of the line in miles.

Column 11 gives the reactance, in ohms per ml. of wire, at 50 cycles, *i.e.* $2\pi n L$, or $314L$, where L is in henries or (mH / 1 000) (*see* examples in § 299 (single-phase) and § 302 (3-phase)). The value in cols. 10 and 11 differ so little that they are only given for alternate gauges; interpolation between the two neighbouring values *for the same spacing* will give the figures if necessary, but, as the impedance is given all through, these columns will not be required often.

For any other frequency the figures must be multiplied by (Actual frequency / 50). Thus for No. 3 S.W.G. and 18-in. spacing, the reactance per ml. at 60 cycles will be 0·628 Ω per ml.; at 125 cycles 1·31 Ω.

Column 12 gives the total impedance at 50 cycles in ohms per ml. of wire, *i.e.* $\sqrt{\{\text{resistance}^2 \ (col.\ 8) + \text{reactance}^2 \ (col.\ 11)\}}$.

TABLE 44.—*Constants of Hard-drawn Copper Wire (50 Cycles in Cols. 10 to 16).*

FOR EXPLANATORY NOTES *see* p. 429.

Size of Wire. S.W.G.	Dia. of Wire. In.	Area of Wire. Sq. In.	Weight of Wire. Lbs. per Ml.	Tensile Strength. Lbs.	Permissible Tension. Lbs. (For Factor of Safety = 5.)	Resistance, at 60° F. Ohms per Yd.	Resistance, at 60° F. Ohms per Ml.	Spacing Between Centres. Ins.	Inductance. Millihenries per Ml.	Reactance. Ohms per Ml. of Wire.	Impedance. Ohms per Ml. of Wire.	Single-Phase. Capacity. Microfarads per Ml. Run.	Single-Phase. Charging Current, at 10 000 V Between Wires. Amperes per Ml. Run.	Three-Phase. Capacity, 1 Wire to Neutral (= Y-Capacity of Whole Line). Microfarads per Ml. Run.	Three-Phase. Charging Current, at 10 000 V Between Wires (= 5 775 V to Neutral). Amperes per Ml. Run.
1.	*2.*	*3.*	*4.*	*5.*	*6.*	*7.*	*8.*	*9.*	*10.*	*11.*	*12.*	*13.*	*14.*	*15.*	*16.*
7/0	0·500	0·196	3 995	11 000	2 200	0·000 125 0	0·220	12	1·32	0·415	0·470	0·011 5	0·036 1	0·023 0	0·041 7
					2 750 *			18	1·46	0·459	0·509	0·010 5	0·033 0	0·021 0	0·038 0
								24	1·55	0·487	0·534	0·009 7	0·030 5	0·019 5	0·035 2
								36	1·68	0·528	0·572	0·009 0	0·028 2	0·018 0	0·032 6
6/0	0·464	0·169	3 441	9 500	1 900	0·000 144 9	0·255	12	—	—	0·494	—	—	0·022 6	0·040 9
					2 370 *			18	—	—	0·530	—	—	0·020 5	0·037 2
								24	—	—	0·555	—	—	0·019 3	0·034 9
								36	—	—	0·593	—	—	0·017 7	0·032 0
5/0	0·432	0·147	2 983	8 200	1 640	0·000 167 1	0·294	12	1·37	0·431	0·522	0·011 1	0·034 8	0·022 2	0·040 2
					2 050 *			18	1·50	0·471	0·555	0·010 1	0·031 7	0·020 2	0·036 6
								24	1·59	0·499	0·579	0·009 5	0·029 8	0·019 0	0·034 4
								36	1·73	0·544	0·618	0·008 7	0·027 3	0·017 5	0·031 6
4/0	0·400	0·126	2 558	7 000	1 400	0·000 194 9	0·343	12	—	—	0·558	—	—	0·021 8	0·039 5
					1 750 *			18	—	—	0·590	—	—	0·019 7	0·035 6
								24	—	—	0·612	—	—	0·018 7	0·033 8
								36	—	—	0·650	—	—	0·017 2	0·031 1

TABLE 44 (*continued*).

3 / 0	0·372	0·109	2 212	6 100	1 220 *1 520* *	0·000 225 6	0·397	12	1·42	0·446	0·598	0·010 7	0·033 6	0·021 4	0·038 8
								18	1·55	0·487	0·628	0·009 7	0·030 4	0·019 5	0·035 2
								24	1·64	0·515	0·650	0·009 2	0·028 8	0·018 4	0·033 3
								36	1·73	0·559	0·684	0·008 5	0·026 7	0·017 0	0·030 8
2 / 0	0·348	0·095	1 935	5 300	1 060 *1 330* *	0·000 258 0	0·454	12	—	—	0·640	—	—	0·021 1	0·038 2
								18	—	—	0·670	—	—	0·019 3	0·034 9
								24	—	—	0·694	—	—	0·018 1	0·032 8
								36	—	—	0·726	—	—	0·016 8	0·030 4
1 / 0	0·324	0·082	1 678	4 600	920 *1 150* *	0·000 297 7	0·524	12	1·46	0·459	0·698	0·010 3	0·032 4	0·020 7	0·037 5
								18	1·59	0·499	0·724	0·009 5	0·029 8	0·019 0	0·043 4
								24	1·69	0·532	0·747	0·008 9	0·028 0	0·017 9	0·032 4
								36	1·82	0·572	0·776	0·008 2	0·025 8	0·016 5	0·029 8
1	0·300	0·071	1 439	4 000	800 *1 000* *	0·000 347 1	0·611	12	—	—	0·770	—	—	0·020 4	0·037 0
								18	—	—	0·794	—	—	0·018 7	0·033 8
								24	—	—	0·814	—	—	0·017 6	0·031 8
								36	—	—	0·840	—	—	0·016 3	0·029 1
2	0·276	0·060	1 218	3 350	670 *840* *	0·000 410 2	0·722	12	1·52	0·478	0·866	0·010 0	0·031 4	0·020 0	0·036 2
								18	1·64	0·515	0·888	0·009 2	0·028 8	0·018 4	0·033 3
								24	1·74	0·547	0·906	0·008 6	0·027 0	0·017 3	0·031 2
								36	1·87	0·587	0·931	0·008 0	0·025 2	0·016 1	0·029 1
3	0·252	0·050	1 015	2 800	560 *700* *	0·000 492 0	0·866	12	—	—	0·994	—	—	0·019 6	0·035 5
								18	—	—	1·012	—	—	0·018 0	0·032 6
								24	—	—	1·030	—	—	0·017 0	0·030 8
								36	—	—	1·052	—	—	0·015 8	0·028 6
4	0·232	0·042	860	2 350	470 *585* *	0·000 580 1	1·021	12	1·57	0·494	1·134	0·009 6	0·030 1	0·019 2	0·034 8
								18	1·70	0·534	1·152	0·008 8	0·027 6	0·017 7	0·032 0
								24	1·79	0·5[illegible]4	1·166	0·008 4	0·026 4	0·016 8	0·030 4
								36	1·92	0·605	1·187	0·007 8	0·024 5	0·015 6	0·028 2
5	0·212	0·035	718	1 950	390 *486* *	0·000 694 8	1·223	12	—	—	1·322	—	—	0·018 9	0·034 2
								18	—	—	1·338	—	—	0·017 4	0·031 4
								24	—	—	1·352	—	—	0·016 5	0·029 8
								36	—	—	1·368	—	—	0·015 3	0·027 6
6	0·192	0·029	589	1 620	324 *405* *	0·000 847 0	1·491	12	1·63	0·512	1·576	0·009 2	0·028 9	0·018 5	0·033 4
								18	1·76	0·554	1·591	0·008 5	0·026 7	0·017 1	0·030 9
								24	1·86	0·584	1·602	0·008 0	0·025 2	0·016 1	0·029 1
								36	1·98	0·622	1·615	0·007 5	0·023 6	0·015 1	0·027 2
10	0·128	0·012 9	262	800	160 *200* *	0·001 906 0	3·354	12	1·76	0·553	3·400	0·008 5	0·027 7	0·017 1	0·031 0
								18	1·89	0·594	3·410	0·007 9	0·024 8	0·015 8	0·028 6
								24	1·98	0·622	3·415	0·007 5	0·023 6	0·015 1	0·027 2
								36	2·12	0·656	3·425	0·007 0	0·022 0	0·014 1	0·025 4

* The old B.O.T. Regulations required a factor of safety of 5, but a factor of safety of 4, under the worst conditions, is sufficient in practice, and may be adopted when the Regulations are not applicable. The permissible tension is then as given by the italicised figures in col. 6. The new Regulations are referred to in § 324.

Thus for a single-phase line the figure must be multiplied by the length of wire in miles (lead + return), while for 3-phase the impedance of one wire is found from the table by multiplying by the route length. For other frequencies the value can be worked out from the formula by obtaining the reactance in the manner explained above.

Columns 13 and 14 relate to single-phase transmission; the former gives the capacity per ml. run of line, so when multiplied by the route length will give the capacity of the whole line. The formula and an example are given in § 305.

Column 14 gives the charging current per ml. run of line, at 50 cycles and 10 000 V between wires; *see* example in § 305. For any other frequency or pressure the figures should be multiplied by (Frequency / 50) or (Pressure / 10 000) as the case may be. Thus the charging current of a line 110 mls. long, consisting of two No. 3 S.W.G. wires spaced 18 ins. apart, at 60 or 125 cycles respectively and 6 600 V, will be $0{\cdot}028\,2 \times 110 \times [60 \text{ (or } 125) / 50] \times (6\,600 / 10\,000) = 2{\cdot}46$ or $5{\cdot}13$ A, as the case may be.

Columns 15 and 16 refer to 3-phase lines. Col. 15 gives the capacity per ml. of 1 wire to the neutral point, which is also the Y-capacity of the whole line per ml. run. Col. 16 gives the charging circuit per ml. run of line at 50 cycles and 10 000 V between wires, or 5 775 V to neutral. It is the charging current of a corresponding single-phase line $\times\ 2 / \sqrt{3}$. An example is given in § 306. For other frequencies and pressures multiply by (Frequency / 50) and by (Line pressure / 10 000) or (Pressure to neutral / 5 775).

308. Constants of Hard-drawn Aluminium Wire.

—If required, a table corresponding to Table 44, but for hard-drawn aluminium wires can be prepared by aid of the following notes:—

Modifications Required to Adapt Table 44 for Aluminium.

Columns 1-3 are applicable regardless of the material.

Column 4. The figures in this column must be multiplied by 0·305 to give the weight per ml. of aluminium wire, *e.g.* the weight of No. 1 S.W.G. wire is about $1\,439 \times 0{\cdot}305 = 439$ lbs. per ml.

Columns 5 and 6. The ultimate tensile strength and the permissible tension for aluminium wires are about 0·53 the values given for copper wires of the same gauge size (*not* of the same conductivity).

Columns 7 and 8. The resistance values for hard-drawn aluminium are about 1·63 times those for copper wires of the same gauge size.

Column 9. In any particular line the spacing between aluminium conductors is generally greater than it would be using copper wires; this, however, does not affect the use of the table.

Columns 10 and 11. The values given for copper apply also to aluminium (or any other non-magnetic material) for the same size and spacing.

Column 12. The values for aluminium will be calculated from $\sqrt{\{\text{resistance}^2}$ (*new col. 8*) + reactance^2 (*col. 11. Table 44*)$\}$.

Columns 13-16. The values for copper apply also to aluminium for the same size and spacing of wires.

For data concerning the mechanical constants of aluminium wire *see* § 331.

309. Constants of Steel Wires.

—Steel conductors offer

TABLE 45.—*Constants of Steel Conductors.*

Size and Description of Conductor.	Cross-section Circ. Mils.* (sq. ins. in brackets).	Temperature Coefficient of Resistance per 1° C, at 20° C.	Test Frequency, Cycles / Sec.	Test Current, Amperes.	Steady Temperature Rise Above Air at 20° C., in °C.	True (D.C.) Resistance † (Single Conductor) Ohms / Mile. (A).	Effective (A.C.) Resistance † (Single Conductor) Ohms / Mile. (B).	Skin Effect Ratio (= B / A).	Internal Inductance (Single Conductor) Millihenries per Mile.	Internal Inductance Ratio.‡
3/8" High-strength strand	99 960 (0· 078 5 sq. in.)	0· 003 38	60	5	0·2	5·84	5·87	1· 006	1·35	13·1
				15	1·8	5·87	5·94	1· 011	1·48	14·3
				25	4·6	5·93	6·03	1· 016	1·61	15·6
			25	5	0·2	5·82	5·83	1· 002	1·36	13·2
				15	1·6	5·85	5·86	1· 001	1·49	14·5
				25	—	5·96	5·99	1· 005	1·65	15·9
1/2" Siemens-Martin strand	177 600 (0· 139 4 sq. in.)	0· 003 33	60	5	0·2	3·36	3·40	1· 012	1·42	13·8
				15	1·2	3·38	3·43	1· 015	1·52	14·7
				25	2·8	3·40	3·47	1· 021	1·63	15·8
			25	5	0·2	3·36	3·37	1· 004	1·47	14·2
				15	1·2	3·37	3·39	1· 006	1·55	15·0
				25	3·0	3·39	3·41	1· 007	1·66	16·0
3/8" Siemens-Martin strand	99 960 (0· 078 5 sq. in.)	0· 003 48	60	5	0·4	5·40	5·44	1· 008	1·40	13·6
				15	2·4	5·44	5·49	1· 011	1·58	15·3
				25	6·6	5·52	5·62	1· 017	1·73	16·7
			25	5	0·4	5·41	5·42	1· 002	1·40	13·5
				15	3·0	5·45	5·47	1· 004	1·58	15·3
				25	6·4	5·53	5·57	1· 006	1·73	16·8
1/4" Siemens-Martin strand	46 900 (0· 036 8 sq. in.)	0· 003 09	60	5	0·6	12·22	12·25	1· 002	1·46	14·1
				15	5·4	12·46	12·54	1· 006	1·65	15·9
				25	17·8	12·91	13·04	1· 009	1·85	17·9
			25	5	0·6	12·17	12·20	1· 001	1·47	14·2
				15	7·4	12·49	12·51	1· 002	1·65	15·9
				25	18·2	12·94	13·02	1· 006	1·88	18·2
3/8" Standard strand (relatively soft)	109 400 (0· 085 9 sq. in.)	0· 005 70	60	5	0·2	3·62	3·91	1· 080	3·24	31·4
				15	2·0	3·62	4·37	1· 207	4·69	45·4
				25	5·0	3·73	5·63	1· 512	6·33	61·3
			25	5	0·2	3·60	3·73	1· 036	3·90	37·7
				15	2·0	3·64	4·07	1· 117	6·19	59·9
				25	5·6	3·70	4·62	1· 250	8·54	82·7

* 1 circ. mil. = 0· 785 4 sq. mil. ; 10 000 circ. mils. = 0· 007 85 sq. in.
† At the steady temperature attained by the wire when carrying the stated current, in air at 20° C.
‡ The internal inductance ratio = (internal inductance) / (internal inductance assuming unit permeability).

economic advantage in the case of short or medium-length lines carrying relatively small amounts of energy at relatively high voltage, so that the pressure drop and power loss in the line are not above the permissible limit. Steel conductors can also be used in short or medium-length lines in which the minimum size of conductor is fixed by considerations of corona loss, and not by the effective resistance of the line. On long spans across rivers, valleys, etc., it may be necessary to use steel to secure sufficient mechanical strength in the line (§ 331). The harder grades of steel have higher tensile strength and higher ohmic resistance than softer steel; on the other hand, the magnetic permeability is also lower hence the skin effect (§ 38) and internal inductance are less than in the softer steel. The effective resistance to A.C. is lower at 25 than at 50 cycles / sec. (§ 135) and is generally lower in soft than in hard steel at all currents up to 25 A in a $\frac{3}{8}$ in. stranded conductor. The data in Table 45 are from tests made to the order of the Indiana Steel and Wire Co. (*see also El. Wld.*, Vol. 80, p. 872.)

310. Insulated Cables; Inductance, Reactance, and Impedance.—The coefficient of self-induction, L, of insulated cables is found by the same formula as is given (§ 299) for overhead lines, *viz.* $L = \{0{\cdot}080\,5 + 0{\cdot}741 \log [(d - r) / r]\}$mH per ml., and the reactance and impedance are determined in the same way as before. Here r is of the same order of magnitude as the distance between wires, d, and becomes important; though the value of d increases with the pressure, owing to the greater thickness of dielectric required. For cables with conductors of 0·03 sq. in. (equivalent roughly to No. 6 S.W.G. solid or 7 / 15 stranded) the impedance may be taken as equal to the resistance, and this holds good for all smaller sizes. For a cable of 0·25 sq. in. the ohmic resistance may be multiplied by the following factors to give the impedance at 50 cycles, *viz.*: 660 V cable, 1·18; 2 200 V, 1·20; 3 300 V, 1·21; 6 600 V, 1·23; 11 000 V, 1·27. It is better to obtain actual figures from the manufacturers in all cases where the impedance must be taken into account.

311. Paper-insulated Cables; Capacity and Charging Current.—In the case of overhead wires the dielectric was air; in cables it may be bitumen, india-rubber, paper, etc. (§ 287), and the capacity varies directly as the specific capacity of the material used (*see* Table 7, p. 78). The capacity of *concentric* paper-insulated cables is about $[0{\cdot}1\text{-}0{\cdot}12 / \log (D / d)]$ μF per

ml., where D is the diameter over the insulation surrounding the inner conductor and d is the diameter of inner conductor. The charging current is found as for 2-wire aerial lines (§ 305). For 3-phase, 3-core (*shaped-conductor*), paper-insulated cables, made in accordance with B.E.S.A. Report No. 7, 1922, for a mesh system (*i.e.* with equal insulation 'core-to-core' and 'core-to-lead'), the *Henley Manual* gives a table from which Table 46 has been calculated.

TABLE 46.—*Electrostatic Capacity of 3-core Paper-insulated Lead-covered Cables with Shaped Conductors and Equal Insulation Core-to-core and Core-to-lead.*

Note.—C = Capacity per ml., one wire against others bunched and earthed
= also, the wire to earth capacities for single-phase circuits.
C_y = star or Y-capacity, *i.e.* the working capacity per ml. for 3-phase circuits.

For cables with *circular conductors*, the capacities will be about 10 % less than shown below.

For cables with *less insulation core-to-lead* than core-to-core, as used for *star systems with earthed neutral*, the capacities will be about 15 % greater than shown below.

Conductor.		Capacity per Ml. of Cable, for Voltage (between Conductors).									
		660 V.		2 220 V.		3 300 V.		6 600 V.		11 000 V.	
Nominal Area. Sq. In.	No. of Wires and Dia. In.	C. μF.	C_y. μF.	C. μF.	C_y. μF.	C. μF.	C_y. μF.	C. μF.	C_y. μF.	C. μF.	C_y. μF.
0·022 5	7 / ·064	0·44	0·53	0·39	0·47	0·35	0·42	0·30	0·37	0·23	0·28
0·030	19 / ·044	0·49	0·60	0·42	0·51	0·39	0·47	0·32	0·39	0·25	0·30
0·040	19 / ·052	0·56	0·69	0·46	0·56	0·42	0·51	0·35	0·42	0·28	0·33
0·060	19 / ·064	0·67	0·81	0·53	0·63	0·49	0·60	0·39	0·47	0·32	0·39
0·075	19 / ·072	0·76	0·91	0·58	0·70	0·53	0·63	0·42	0·51	0·35	0·42
0·100	19 / ·083	0·84	1·02	0·65	0·79	0·58	0·70	0·46	0·56	0·37	0·46
0·120	37 / ·064	0·90	1·09	0·70	0·86	0·63	0·77	0·49	0·60	0·40	0·49
0·150	37 / ·072	0·95	1·16	0·76	0·91	0·69	0·83	0·55	0·67	0·44	0·53
0·200	37 / ·083	1·00	1·21	0·83	1·00	0·77	0·93	0·60	0·72	0·49	0·60
0·250	37 / ·093	1·05	1·28	0·90	1·09	0·83	1·00	0·65	0·79	0·53	0·63

The charging current is found from the formula already given for 3-phase aerial lines (§ 306).

Thus for a 3-core cable, 10 mls. long, having conductors 0·1 sq. in. (about equivalent to the No. 3/0 solid wire in §§ 302, 306) the charging current at

6 600 V and 50 cycles will be $[0{\cdot}000\,314 \times (6\,600/\sqrt{3}) \times 0{\cdot}56 \times 10] = 6{\cdot}7$ A. This is no longer negligible; it represents $6{\cdot}7 \times 6\,600 \times 1{\cdot}73/1\,000 = 76{\cdot}8$ kVA from the generator solely to charge the line to full pressure.

Welbourn (*Jour. I.E.E.*, Vol. 53, p. 95) estimates that about 2 500 kVA of plant would be required merely to charge a 30-ml. network of 30 000 V cable in a system operating at 50 cycles; taking into account also the cost of transformers, switch-gear, etc., it is doubtful whether higher pressures than 33 000 V are commercially justifiable in 3-core, 50-cycle cables.

The question of charging currents is of particular importance in 'intersheath' cables (§ 289). The capacity between intersheath and outer lead sheath is larger than in an ordinary cable, but the capacity currents on inner and outer surfaces of the intersheath are in opposite directions, so that the net intersheath current is relatively small. The capacity current in the outer sheath equals, however, the sum of the capacity currents in all the intersheaths and in the conductor itself. At 100 kV, 50 cycles, the charging current in the intersheath cable specified in § 289 is: (*a*) in conductor, 3·9 A; (*b*) in intersheath, 7·4 A; (*c*) in lead sheath, 11·3 A per ml. Though only 0·05 in. in thickness, the intersheath will carry the charging current for more than 3 mls. of cable when that current is fed from one end, or for 6 ml. feeding from both ends. Only short lengths of intersheath cable are likely to be used in the near future, but there is no great difficulty in arranging to feed in charging current at intervals when that becomes necessary.

312. Dielectric Loss in Cables.—In all cables there is some leakage of current between cores and between cores and earth through the ohmic resistance of the insulation; this resistance is however so high, when the cable is in good service condition, that the leakage current is extremely small and the I^2R loss in the insulation (as distinct from that in the conductor) is insufficient to heat the insulation appreciably. On the other hand, if the insulation be damp, the leakage current and the heating caused thereby increase to a dangerous extent. In D.C. cables the leakage current is the only loss in the dielectric, but the charging current has also to be considered where cables carry alternating current. Every cable is in effect a condenser and, if its power factor were zero, the charging current would be quite 'wattless.' Actually, energy is dissipated by dielectric hysteresis (§ 60) and

P.F. of the cable is, say, 2 or 3 °/。 (lower sometimes *), so that re is a small watt-component in the charging current, and this ponent heats the dielectric.

The power absorbed by the dielectric of a cable increases with square of the applied voltage and, after decreasing as the perature rises to 35° C., it thereafter increases rapidly with perature; for example, the dielectric loss in certain 13 200 V, ore cables at 60 cycles was about 0·75 kW / ml. at 50° C.; 25 kW at 70° C.; and 6·25 kW at 100° C. The dielectric loss modern 33 000 V, 3-core cables at 50 cycles, 60° C. is about ·2 kW per ml.

313. Calculations for Three-Phase Line with Transformers.—Where extra high pressure is used on the transmission it is generally stepped up at the generating station and down ain at the receiving end. About 3 °/。 (more or less) is lost in h transformation at full load, and in working out a system on lines of § 302 this must be taken into account. If the transmation ratio is, say, 25 to 1 then, when the pressure is either ised or lowered, the inverse ratio must be applied to the current; is can be done subsequently, as it simplifies matters if the line ssure is used in the calculations throughout.

For example, assume that 3 000 kW are to be delivered at the end of a 3-phase 15 mls. long, with a line loss of about 10 °/。, the power factor of the load ing 0·85 and the pressure at the receiving end 1 000 V between lines. Then h a transformer ratio of 25 to 1 the equivalent line pressure will be 25 000 V d the pressure to neutral will be 14 430 V. The energy delivered by each nch will be 1 000 kW, and the current (1 000 × 1 000 / 0·85 × 14 430), or say A.

Proceeding as in §§ 302, 306 the nearest size of wire will be No. 4 S.W.G., d each branch may be assumed to have the following approximate characters: Resistance = 16·05 Ω; inductance = 25·62 mH; reactance = 9·66 Ω; pacity = 0·264 μF. These data may either be worked out or taken from Table , assuming suitable spacing.

The transformers at both ends are assumed to have the following characters: Efficiency, 97 °/。; copper loss, 1 °/。; hysteresis, $1\frac{1}{2}$ °/。; reactance, $3\frac{1}{2}$ °/。; agnetising current, 4 °/。. As the power factor of the load (cos ϕ) is 0·85, the inction factor (sin ϕ) will be 0·52.

* Low, P.F. is particularly important in high-voltage, high-power cables beuse each 1 °/。 of the total kVA then represents a large amount of energy and erefore appreciable heating of the dielectric, the break-down strength of which creases as the temperature rises. It is now (1923) possible to make 44 000 V, core cables with a P.F. not exceeding 1 °/。 at temperatures up to 55° or 60° C. e P.F. of air-core telephone cables, in which paper is used only as a mechanical acer to hold the wires apart, may be as low as 0·2 °/。.

TABLE 47.—*Voltage Components, Current and Power in 3-Phase Overhead Line with Transformers.*

	Voltage.		Current.	Power.
	Energy.	Induction.		
	V	V	A	
Secondary circuit—				
Energy component 85 % of 14 430 V	12 265	—	—	Total power at end 12 265 × 82 × 3 = 3 017 kW.
Induction component 52 % of 14 430 V	—	7 503	—	
Current	—	—	82	
Step-down transformers—				
Resistance loss 1 % of 14 430 V	144	—	—	Loss 80 kW.
Reactance loss $3\frac{1}{2}$ % of 14 430 V	—	505	—	
Hysteresis loss $1\frac{1}{2}$ % of 82 A .	—	—	1·2	
Data at high-tension side of transformer	12 409	8 008	83·2	Power to transformers 3 097 kW.
Line—				
Resistance loss (16·05 × 83·2) V	1 336	—	—	Loss 334 kW.
Reactance loss (9·66 × 83·2) V .	—	804	—	
$\sqrt{(13\,745^2 + 8\,812^2)} = 16\,329$ V at terminals of step-up transformer	13 745	8 812	83·2	Power to line 3 431 kW.
Step-up transformers—				
Resistance loss 1 % of 16 329 V	163	—	—	Loss 94 kW.
Reactance loss $3\frac{1}{2}$ % of 16 329 V	—	572	—	
Hysteresis loss $1\frac{1}{2}$ % of 83·2 A .	—	—	1·3	
$\sqrt{(13\,908^2 + 3\,984^2)} = 17\,030$ V at generator terminals . .	13 908	9 384	84·5	Power, 3 525 kW.

The working may now be set out as in Table 47, from which it will be seen that the pressure between lines at the generator terminals is 17 030 × $\sqrt{3}$ or 29 450 V and the current 84·5 A; if the ratio of the transformation is 25 to 1, then the actual values will be 1 180 V and 2 110 A. The efficiency of transmission is (Power delivered / Power generated) = 3 017 / 3 525 or $85\frac{1}{2}$ %. The P.F. of the whole circuit will be (kW delivered / kVA generated) = 3 017 / 4 320 or 0·7.

This method of calculation is applicable to any installation of transformers on an A.C. system.

314. Star and Delta Connections of Generator.—Hitherto we have dealt with a 3-phase 3-wire line and the conditions in it, but largely by reference to the pressure from any phase wire to

the neutral point. Now, as any two wires act as the return for the third, at both ends of the line the phase wires must in some manner be interconnected. For instance, at the generating end there are the coils on the generator; if the pressure is stepped up or down there are the coils on the transformers; at the receiving end there may be the stator coils of a motor, or the phases may be used as separate single-phase circuits. Either the star or the delta arrangement may be used (§ 143).

First consider the coils of a generator and the wires leading from them, in the example of 3-phase transmission with P.F. 0·88 at the generator end discussed in §§ 301-303.

With *star connection* one end of each generator coil connects on to one wire of the line, so the current must obviously be the same in coil and wire, *viz.* 102 A. The other ends of the three coils are all joined together at the neutral point (which may or may not be 'earthed'), so the pressure developed in each coil will be the pressure from line wire to neutral, *viz.* 3 885 V. The power generated in each coil is $IE \cos \phi$ *i.e.* $102 \times 3\,885 \times 0{\cdot}88 = 352$ kW, or 1 056 kW for the whole generator.

With *delta connection* the ends of the generator (or transformer) coils are connected in delta (Δ) or triangle, and the neutral point may be considered as in the middle of the triangle; the line wires take off from the junction points (as shown in Fig. 36, § 143). It will be seen that each line wire is being supplied with current by two generator coils, and the current in each coil will be (Line current $/ \sqrt{3}) = 102 / 1{\cdot}73$ or 58·8 A. As each generator coil is connected directly between two line wires the pressure developed in it must be the full line pressure or 6 730 V. Here also the power generated in each coil is $IE \cos \phi$, *i.e.* $58{\cdot}8 \times 6\,730 \times 0{\cdot}88 = 352$ kW or 1 056 kW for the whole generator.

315. Extra High Voltage Transmission.—It will be seen from the general formula in § 295 that the sectional area of conductor required to transmit any stated amount of power for a given distance with specified loss varies inversely with the square of the voltage between lines. In other words the cost of the conductors themselves varies inversely with the square of the transmission voltage. This statement holds good in practice, at least up to the voltage at which corona (§ 316) requires the use of a larger conductor than would otherwise be needed. Alternatively, the amount of power which can be transmitted by conductors of stated size increases with the square of the voltage between lines. Thus, according to requirements, we can use smaller conductors or fewer circuits in the transmission system by working at higher voltages. The cost of towers and of wayleaves is reduced by reducing the number of circuits but, on the other hand, higher voltages involve greater outlay upon insulators and more costly

towers, if the spacing between conductors has to be increased. In practice it is generally found that the cost of transmission lines for pressures higher than, say, 66 000 V increases in direct proportion with the line voltage. As the carrying capacity increases with the square of the line voltage there is a wide margin in favour of higher voltages wherever the amount of power and the distance of transmission justify the higher cost of transformers and switchgear for the higher pressure. The relative merits of different voltages must be determined by comparing detailed estimates for the alternative schemes, and an allowance (varying with circumstances) must be made for the fact that the security of supply is reduced when working at higher voltage over fewer circuits.

In Great Britain there is no water-power of any considerable magnitude, excepting tidal power which is still of problematical utility. Energy developed in coal-burning or other thermal power stations cannot economically be transmitted more than, say, 50-100 mls. because this distance brings us either outside the industrial area or into an adjoining coalfield. It is therefore improbable that pressures exceeding 40-60 kV will be required for overhead transmission in Great Britain. On the Continent of Europe and most other parts of the world, excepting the United States, 100 to 120 kV appears to be about the economic limit of voltage for overhead transmission, this pressure being sufficient to carry hydro-electric power economically to industrial areas capable of absorbing it.

The United States, with enormous industrial demands at long distances from equally large water-power projects, is the home of 'super-transmission' schemes. At the time of writing, the Southern Californian Edison Co. is converting its two 150 kV, 55 000 kW, 3-phase circuits from the Big Creek hydro-electric development to Los Angeles (240 mls.) for operation at 232 kV, thus increasing the power capacity of the lines.

Tests by the General Electric Co. (Schenectady) in 1921 demonstrated that power could be transformed to 1 100 kV at 60 cycles / sec. and transmitted at this pressure, using tubular conductors of 4 ins. dia. to avoid corona (§ 316). The spark-over distance between points at 1 000 kV is about 105 ins. This investigation is mainly of interest as regards pressure testing and the determination of physical laws. It demonstrates, however, that power transmission at commercial frequencies is feasible at much higher pressures than yet used. Probably power could be transmitted 1 000 mls. with equipment representing a mere extension of present-day practice, but the cost of tubular conductors and of the insulators required would be abnormally high, and it is, at present, generally possible to sell within a radius of 200 or 300 mls. all the hydro-electric power which can economically be developed. Save for this general consideration, however, there is nothing to indicate that existing transmission pressures and distances will not be greatly exceeded (§§ 318, 319).

316. Corona Discharge.—The term 'corona' is generally applied to the discharge which takes place from a charged body in air when the electrostatic stress is sufficient to ionise the

layers of air in contact with the body, thus rendering them electrically conducting. At higher values of the electrostatic stress there occurs a brush discharge or, if the stress be high enough, flash-over to an adjacent body. Corona discharge occurs from overhead transmission conductors at high pressures (rarely below 100 kV between phases with usual sizes and spacings of conductors), and it is also liable to occur from the sharp edges of charged metal in oil-immersed apparatus, and in air films in or between layers of solid dielectric. In the latter case, as in cables, it quickly deteriorates the insulating material by its heating and chemical effects and so leads to break-down.

In high-voltage cables and coil insulation air films must be eliminated at all costs (§ 79). In switchgear, transformers, mercury rectifiers, and other apparatus where corona might give trouble, the discharge may be eliminated by the use of well-rounded parts (so as to reduce the electrostatic stress, § 288) or the possible source of corona may be separated from the danger space (*e.g.* a space filled with air and oil vapour) by an earthed metallic screen. The factors determining the occurrence of corona on overhead transmission lines are shown in the formula below; increasing the distance between conductors is a costly and relatively ineffective method of reducing the loss; in any particular case the voltage and frequency are fixed, and atmospheric conditions are beyond control; the only remaining method of reducing the loss is to increase the diameter of the conductor, *e.g.* by the use of steel-cored copper cable or aluminium (§ 331). Corona leads to corrosion of conductors by causing the formation of nitrous acid, and the power dissipated by the discharge may be a serious factor.

The following data are due to F. W. Peek:* The *disruptive critical voltage* of air (at which voltage corona actually commences in practice, due to dirt and irregularities on the surface of the conductor) is given by—

$$e = gMr\delta \log_e \frac{S}{r},$$

where e = disruptive critical voltage, in kV (R.M.S.) to neutral;
g = disruptive pressure gradient of air;
= 21·1 kV (R.M.S.) per cm. for all conductors and commercial frequencies at 25° C. and 76 cms. barometric height;
M = 1·0 for polished wires; 0·98-0·93 for rough or weathered wires; 0·87-0·83 for 7-strand conductors;

* *Trans. Amer. I.E.E.*, Vol. 30, p. 1889; Vol. 31, p. 1051; Vol. 32, p. 1767.

r = radius of conductor, in cms.;
δ = an air density factor = $3{\cdot}92\, b\, /\, (273 + t)$, where b = barometric height in cms.; t = temperature in °C.;
S = distance between centres of conductors, in cms.;
log = $2{\cdot}303 \log_{10}$.

The *power loss by corona* is given by—

$$P = \frac{344}{\delta} f \sqrt{\frac{r}{S}} (E - e)^2 \times 10^{-5},$$

where P = power loss, in kW per km. per conductor;
f = cycles per sec.;
E = R.M.S. pressure between line and neutral, in kV; and the other symbols have the same meanings as before.

(*Note.*—1 in. = 2·54 cms.; 1 ml. = 1·61 km.)

Within the range of the tests (47-120 cycles) the power loss by corona varies directly with the frequency. At zero frequency (D.C.) the loss is from $\frac{1}{4}$-$\frac{1}{2}$ the loss at 60 cycles for the same *maximum* voltage.

The above formulæ relate to fair weather conditions. To determine the power loss in foul weather, take e = 80 °/₀ of the fair weather value. The operating voltage should not exceed e or the corona loss will be very high during fog, rain, or snow, or when the conductor surface is rough.

317. **Thury Constant-current System.**—This system of direct-current transmission employs the same general principles as are applied in constant-current series-arc circuits (Chapters 19, 25), but much higher pressure and power are now involved. A number of series-wound generators (§ 138) are connected in series to supply a number of loads also in series, the loads being generally motors driving auxiliary generators in substations, and the voltage of the main generators being varied to maintain the current constant. This system is used fairly extensively on the Continent, where constant currents from 50 up to 450 A are used in various installations with maximum circuit pressures up to 100 kV. The Moutiers-Lyons scheme is the most important yet erected.* In England, the Metropolitan Electric Supply Co. has a Thury transmission designed for 10 000 kW and a maximum pressure of 100-120 kV, using single-conductor, lead-sheathed cables with core section 0·125 sq. in. and $\frac{1}{2}$ in. of paper insulation. This transmission will ultimately serve an area of 300 sq. mls. or so in Western London, and represents the most

* Much information concerning this, as well as a detailed treatment of the principles, advantages, and disadvantages of the Thury system, is to be found in *General Electric Review*, Vol. 18, p. 1026 *et seq.*; other papers which may be consulted are: *Jour. I.E.E.*, Vol. 38, p. 407; Vol. 39, p. 848; Vol. 51, pp. 443, 640.

economical solution to the problem of supplying an undeveloped but rapidly growing district in which overhead transmission is not considered permissible, whilst underground A.C. transmission would be impracticable.

Though the P.D. between points in the windings of a generator or motor in a Thury circuit may be limited to, say, 3 000 or 5 000 V, the line pressure at this point may be 100 000 V above earth pressure; hence it is necessary to carry the bedplate of the machine on insulators and to place the cement foundation block on insulators and surround it by a filling of asphalt and bitumen. Insulating couplings are necessary between generator and prime mover; and commutators for high pressures are costly and need much attention. Advantages and disadvantages may be thus summarised:—

Advantages.—Economy in distribution due to use of high pressures (§ 315). Possibility of using higher pressure than with A.C. for given insulation strain (§ 298). Inductance, capacity, phase displacement, and voltage surge problems are eliminated, and dielectric loss in cables reduced practically to zero. The only loss of importance is that due to ohmic resistance of the line; the percentage value of this loss is not serious when the constant current for the power available is so chosen that the circuit is normally worked near the limit of practicable voltage. (At present the limiting voltage for D.C. cables is about 150 kV to earth or 300 kV between extreme conductors.) On the other hand, since the current is constant, ohmic losses in the line are also constant, so that the efficiency of a Thury transmission on light loads is low. The aim must be low current and high voltage, *i.e.* minimum ohmic loss and maximum useful load to reduce the percentage importance of the loss.

The earth can be used as return path in a Thury circuit, or it can be 'tapped' to replace the function of a broken-down section of a metallic circuit. The ohmic loss in the earth path is small, but there is a certain liability to electrolytic trouble near the earth plates. Instead of being used as an active conductor, the earth may be used as neutral to limit the voltage, line to earth, to half the total pressure. One or more generators can be connected in series with a Thury circuit at any convenient point, say where there is a waterfall which might be so small as not to justify development on any other system (§ 144). One of the most important advantages of the Thury system is that it provides a flexible and efficient means of interconnecting heterogeneous generating systems (§ 186). By using motor generators consisting of constant-current series motors and A.C. or D.C. generators as may be required, any number of A.C. or D.C. networks can be interconnected, energy being transferred from one to another through the Thury circuit and motor generators; this arrangement has been proposed as a possible solution to the problem of co-ordinating electricity supply in London.

No transformation of pressure is required in a Thury circuit, and no general switchboards are required. The switches used are very simple, machines being short-circuited when idle, and tapped into the circuit when working. The series circuit is never opened, and in place of automatic circuit-breakers there are relays

shifting the brushes to zero in case of generator break-down or accidental open-circuit. There is nothing in a Thury station corresponding to the synchronising of A.C. generators, and the load is shared automatically by all the series generators even with 10 % difference in the speed of the sets.

Disadvantages.—The constant current of the circuit cannot be subdivided, and rotary machines are required to yield A.C. or D.C. for distribution purposes. The insulation of the generator and motor frames is a serious problem. A 500 H.P. motor in a 200 A, D.C. circuit would have to be insulated in its windings for about 3 000 V (to allow for 50 % overload); the frame, however, would have to be insulated from earth for the full line voltage, which might be 100 000 V. High-power, high-voltage machines offer difficulties in the way of commutation; about 5 000 V per commutator is the upper limit at present, so that twenty commutators are required for 100 000 V line pressure. Speed-governors or brush-shifting gear or both are required on constant-current generators to provide for voltage regulation.

Though the commutators, generators, and motor governors and frame insulation are costly items in a Thury system, the cost of transmission conductors is less than for A.C. systems (§ 334), particularly where cables are concerned, and to an even greater degree where the earth is used as one conductor. It is not considered likely that the Thury system will ever compete with long-distance, overhead 3-phase transmission as at present developed, but the constant-current D.C. system is undoubtedly the best where transmission must be effected over considerable distance by underground cable; also it has very valuable application in linking together power schemes which have or have not the same voltage, frequency, etc.

318. Quarter-wave and Half-wave Transmission Lines.—A 'quarter-wave' transmission line is one of such length that the time taken for an alternating current to flow from one end to the other equals one-quarter period of the A.C. concerned; similarly, a 'half-wave' line is of such length that the time occupied equals one-half period of the current. If the velocity of flow be equal to the velocity of light (say, 186 000 mls. per sec.), and if A.C. at 50 cycles per sec. be used, the length of a quarter-wave line is about $186\,000 / (\frac{1}{4} \times \frac{1}{50}) = 930$ mls.; and that of a half-wave line is about 1 860 mls. In terms of the inductance and capacity of the line the length of the quarter-wave line is $1/(4f\sqrt{LC})$ mls., and of the half-wave line $1/(2f\sqrt{LC})$ mls., where f = cycles per sec., and LC = inductance and capacity per ml. If the product LC be increased (*e.g.* by the addition of reactance coils to the circuit and the use of underground cables) the route length of a quarter- (or half-) wave line may be

reduced to a few hundred miles. Lines of these electrical lengths have distinctive properties of considerable value from the point of view of power transmission; and it has been suggested that such lines could be used to advantage for the transmission of power over relatively short distances the line being then 'loaded' as above, or over very long distances, only the natural inductance and capacity of overhead lines being then in circuit. The following notes indicate the possibilities and limitations of the two systems * (*see also* §§ 135 (1) and (4); 158):—

The method at present standard for the transmission of A.C. power consists in the delivery of a variable current (according to the load) at constant voltage. In order to maintain constant voltage at the load, the voltage at the input end of the line must be increased as the load increases, so as to compensate for the higher pressure drop in the line. Where a large amount of power has to be transmitted for long distances a wide range of voltage regulation is required at the supply end, and the power loss in the line is a serious consideration.

The Quarter-wave System.—A quarter-wave line is in resonance (§ 47) on open circuit and the characteristics of the circuit are such that, neglecting resistance, constant current input is required for the maintenance of constant voltage at the delivery end. In practice it would be necessary to increase the current input somewhat to compensate for the higher ohmic loss at higher loads but, fundamentally, the system is one of constant current input and its application would require the use of constant-current alternators (which are not standard machines). As the pressure along the line varies with the load delivered, it is impracticable to tap energy from a quarter-wave line at any intermediate point; the system is only applicable to 'through' transmission of energy from point to point. The route length of a quarter-wave line, with only the inductance and capacity of air lines in circuits, is about 750-900 mls. using 50-cycle current, and 1 500-1 800 mls. using 25-cycle current.

The Half-wave System.—A half-wave line may be regarded as two quarter-wave lines placed end to end. With constant voltage supply at the input end there is, neglecting resistance, constant voltage at the delivery end and constant current at the centre of the line. Maximum voltage in the line is at points about one-quarter the total length of the line from each end and is there equal to the station voltage which would be required in an ordinary A.C. system for transmission over this quarter distance. In other words, the half-wave system makes possible transmission over four times the length of an ordinary transmission line with the same maximum voltage in the circuit.

As the voltage at intermediate points varies with the load the half-wave system is limited to 'through' transmission from end to end, except that supply can also be taken at or near the centre from the constant-current portion of the

---

* For a detailed investigation of the characteristics of long transmission lines, *see Theory and Calculation of Transient Electric Phenomena and Oscillations*, by C. P. Steinmetz (McGraw, Hill Co.). The notes here given are from papers on the basic equations of quarter-wave and half-wave lines, with numerical examples, abstracted from *Rev. Gén. d'Électricité* in *El. Rev.*, Vol. 87, pp. 250 *et seq.*

line. With only the inductance and capacity of overhead lines, the route length of a half-wave line is about 1 500-1 800 mls., using 50-cycle current (3 000-3 600 mls. for 25 cycles), but the route length could easily be reduced to 300 mls. by the use of reactance coils of reasonable dimensions in the case of lines for 10 000 kW or so. For higher power, up to, say, 50 000 kW, extra capacity is also required in the circuit; this could be provided by using condensers and / or some underground cable, but it would generally be sufficient merely to subdivide the line conductors.

The half-wave system could be used with standard (constant-voltage) alternators. Its advantages, compared with a plain transmission, are: (1) Elimination of the effects of inductance and capacity on the voltage regulation required at the supply station; the station voltage is higher than the delivered voltage only by the amount of the ohmic (IR) drop. (2) Longer distance transmission feasible with the same maximum line voltage. (3) Lighter conductors and better voltage regulation for given variations in load kW and P.F. Its disadvantage is that energy cannot be tapped intermediately except at the centre point and there only by special constant-current equipment.

319. Six-Phase Underground Transmission at 100-150 kV. —The system proposed by A. M. Taylor (*Jour. I.E.E.*, Vol. 61, p. 220) employs single-core cables with intersheaths (§ 288) which are utilised for power transmission as well as to relieve the pressure gradient on the insulation near the main core. Two star-connected transformer-secondaries are arranged so as to yield a 6-phase supply, the terminals of which (in sequence) are connected to the central, intermediate, and outer cores of one cable A, and to the corresponding cores of a second cable B. The intermediate point of the 6-phase system, between the points connected to the outer cores, being earthed, and the system being operated at 60 000 V, the P.D. between the central and intermediate cores (and between the intermediate and outer cores) is 30 000 V, whilst that between the outer core and the lead sheathing is 17 800 V.

When the load increased a similar 6-phase system with two cables could be added, the connections being such that the diametral voltages of the two 6-phase systems would combine, making possible the superimposing of single-phase transmission at 123 000 V on the two pairs of cables. Finally, a third 6-phase system could be added (again with its own pair of cables) in such vector relationship that there could be transmitted 6-phase current in each pair of cables, and 3-phase current at 100 000 V (or even 150 000 V) through the three lines, each of which consists of one pair of cables. The use of intersheaths reduces the current flowing through the inner layers of dielectric, where the volume of material is least and the heating consequently greatest, and whence the escape of heat is most difficult. By feeding capacity current to the intersheaths at sub-stations along the route, the transmission of such current through the central cores may be eliminated; also, the capacity current may be made to neutralise the reactance drop due to loads at lagging power factor (§ 159); the A.C. transmission is then as efficient as D.C. transmission, in that it is subject only to ohmic pressure drop.

The increased eddy currents in the lead sheathing of single-core, compared with 3-core, cables are claimed not to be serious provided that the cable centres be not more than 6 or 7 ins. apart; in armoured cables the eddy current loss is a more serious consideration. A supplementary explanation of this system is given in *El. Rev.*, Vol. 92, p. 648.

320. Interconnection of Transmission Systems.—For the reasons outlined in § 186 it is becoming increasingly common to interconnect A.C. transmission systems so that power can be transferred from one to another at will.* The voltage and power factor conditions in the interconnecting line are both important; their relation is discussed fully in a paper by L. Romero and J. B. Palmer (*Jour. I.E.E.*, Vol. 60, p. 287), from which the following points are extracted:—

To obtain any desired division of load between two interconnected A.C. power stations it is necessary to adjust the steam (or water or gas, etc.) supply to the prime movers. Mere adjustment of generator fields, or the raising by other means of the voltage at the 'sending' end of the interconnector, only causes wattless kVA to flow through the circuit, the kW remaining constant except for the additional copper loss in the interconnector (§ 155). Adjustment of voltage, in addition to prime mover control, is sometimes necessary.

When current flows through a circuit having resistance and reactance (such as the interconnector, with or without transformers) there is an impedance drop (IZ) which causes the voltage at the two ends of the circuit to differ in magnitude or phase or both.

If the station voltages are *constant and equal*, the mean P.F. of transmission remains at a constant leading value, and the power factors at the station ends of the interconnector vary (slightly) in opposite directions as the load varies or reverses. Power up to the capacity of the line may be transmitted in either direction without varying the voltage or mean P.F. This method might be used to connect two stations each with a load at or near unity P.F., but most stations are unable to take a bulk supply at leading or unity P.F. without serious disturbance to their operating conditions.

If the station voltages are *constant and unequal*, the P.F. of the transmission varies from lag towards lead as the load increases. This method is suitable only for transmitting power in one direction because a reversal of power would flow at a low leading P.F.

If the station voltages are *varied with load*, by induction regulators boosting transformers (Chapter 17) or other means, the P.F. may be kept constant at any desired value within the available range of voltage variation. This method is necessary in most cases. The use of a boosting device makes possible control of the transmission P.F. without varying the bus bar voltage. Formulæ for determining the P.F. of the line current with given load and voltage boost, or the boost required to transmit a stated load at given P.F., are to be found in the paper (*loc. cit.*).

---

* In the great interconnected transmission networks of the United States, some of the power is transmitted 500 or 600 mls. when there is a local shortage of coal or water.

321. Synchronising Effect of Parallel Transmission Lines.—If two alternators be connected each to one of a pair of transmission lines, which are electrically independent but physically parallel to each other on the same poles or towers, the two circuits have a synchronising effect which tends to hold the generators in synchronism or in anti-phase, according to the arrangement of the line conductors.* In order that the paralleling of apparatus in a sub-station may be helped (instead of being hindered) by the synchronising effect of the transmission lines, the conductors of one line should be placed in phase sequence 1—2—3 down one side of the tower, those of the other line being in sequence 3—2—1. That is to say, similar phases in the two lines should be *diametrically opposite* to each other and not in the same relative positions on each side of the tower. This diametrical relation must, of course, be retained at each transposition of the wires.

322. Wayleaves.—Before any overhead transmission line can be erected it is necessary (in Great Britain) to obtain permission (*a*) from the Ministry of Transport; (*b*) from the owner of the ground traversed. Fortunately, it is now much easier than in the past to obtain the requisite official and private consent. The abolition of the absolute power of veto formerly possessed by local authorities is an important reform.

Under the provisions of the General and Special Acts or Orders relating to the supply of electricity, the consent of the Minister of Transport is necessary before Authorised Undertakers may place any electric line above ground, except within premises in the sole occupation or control of the Undertakers, and except so much of any service line as is necessarily so placed for the purpose of supply. In cases where the Local Authority are not themselves the Undertakers, the further consent of such authority was formerly necessary under the provisions of § 14 of the Electric Lighting Act, 1882, and § 10 of the Schedule to the Electric Lighting (Clauses) Act, 1899, or corresponding provision in any Special Act or Order. The position, however, has been modified by § 21 of the Electricity (Supply) Act, 1919, and where the consent of the Minister is obtained to the placing of any electric line above ground in any case, the consent of the Local Authority is not required; but the Minister before giving consent is required to afford the Local Authority an opportunity of being heard. It also falls to the Minister of Transport to give consents in connection with wayleaves for electric lines whether above or below ground under the provisions of § 22 of the Act of 1919.

As previously indicated, overhead lines, whether erected by Authorised Undertakers or without statutory authority, are subject to Regulations prescribed

---

* This phenomenon and the reason for it are discussed in *Gen. El. Rev.*, Vol. 25, p. 146, and *Electricity*, Vol. 36, p. 588.

by the Electricity Commissioners for securing the safety of the public and for the protection of the lines and works of the Postmaster-General (§ 324).

323. Steel, Wooden, and Concrete Poles.—*Steel Poles.*—For transmission lines, built-up steel lattice poles are the most satisfactory on all counts. For comparatively unimportant or light lines, however, tubular tramway poles are often used, and serve their purpose. These latter are generally used in towns, where lattice poles would take up too much room. Tubular 'Hamilton' telegraph poles have also been extensively used, but in the gauges of metal generally employed for telegraph purposes they are not satisfactory; a much higher factor of safety is required in power lines than will suffice for telegraphs.

On one important point engineers and buyers can ensure their steel poles having the longest possible life, namely, by excluding high-tensile steel, of which poles are sometimes made. Most chemists will agree that high-tensile steels tend to corrode more quickly than either wrought-iron or mild steel; and this is probably due to the higher percentage of manganese and carbon present in high-tensile steel. Mild steel with a tensile strength not exceeding 24·28 tons per sq. in. will give the best results in the direction of the minimum tendency to corrode. Engineers would do well to specify the steel of which their poles are made to fall within this figure (E. J. Fox, *Jour. I.E.E.*, Vol. 52, p. 320).

Wooden Poles, used on several important transmission schemes in India, have proved uniformly unsatisfactory; possibly with proper treatment better results would have been obtained, at any rate at high altitudes, where there are no white ants. In this country they are used to a considerable extent. A compound pole of A-form, built up from two single poles and spread about 1 in 8, is roughly $4\frac{1}{2}$ times as strong as a single pole. Where more room is required the H-form is used, with cross-bracing to give stability. At angles, H-poles or three-legged structures should always be used with stays (§ 326) in both alignments rather than a single stay in the resultant. Concrete foundations may be necessary in bad ground, and if a concrete sheathing be carried up the pole above ground level, rotting at the latter is prevented.

Notes on preservative processes for timber are given in § 86. Statistics from a variety of sources show that creosoting under pressure gives the longest life to timber, *viz.* 20-25 years for poles in temperate climates. The life of poles treated with copper sulphate, zinc chloride, or mercury chloride is given as 12-15 years. The life of wooden poles as hitherto used in India has

been 5 or 6 years. Untreated poles last 10 or 12 years in England, and by proper creosoting a life of 30 years or more, up to 50 years, is attainable.

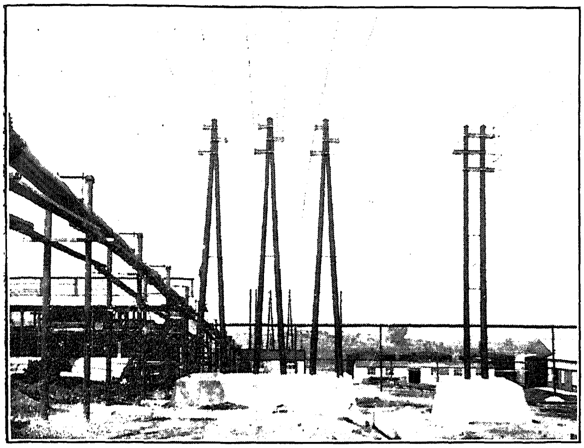
Concrete Poles.—Reinforced concrete poles have been used in a number of cases (particularly in America), as being stronger and more durable than wood, whilst eliminating the constant supervision and repainting required by steel. Concrete poles are heavy, which is a serious matter where transport is difficult; their use is principally in low- and medium-pressure distribution schemes. In some cases a portable pole-making plant and local aggregates may be used with advantage. Tubular construction saves weight with little loss of strength, and provides a convenient duct for cables. A 25-ft. pole tapering from 16 ins. to 7 ins. with $2\frac{1}{2}$-in. walls and twelve $\frac{1}{4}$-in. steel reinforcing rods, weighs about 2 500 lbs., and if set 6 ft. in the ground will withstand safely a pull of 1 000 lbs. applied at the top.

324. **Poles and Wires; Requirements of Rules.**—The first requirement of an overhead line is that it shall be set out properly before erection begins. The position of every pole should be determined; it should be ascertained that the wires in a span will not come too near the ground, especially in the case of tortuous distribution lines in hilly country; the angles should be noted; the nature of the ground where poles and stays must go should be investigated; the height and strength of special poles should be taken out.

In previous editions of this work the Board of Trade Regulations for overhead lines were referred to. The Board has now made way for the Electricity Commissioners and the Regulations are under revision. In theory the Regulations prescribed by the Commissioners, under the power conferred by the existing 'Regulations for securing the safety of the public,' are specially made for each undertaking, and become a part of the Special Order; in fact the new Regulations, like the old ones, will doubtless be practically standard in form. Although the code is not (at the time of going to press) in force the following summary may be taken as substantially correct both for pressures (*a*) not exceeding 650 V, D.C., and 325 V, A.C., and (*b*) exceeding those values.

Line conductors will be of copper or aluminium ordinarily, though steel or other conductors for specially long spans would no doubt be allowed. As regards breaking load, elongation, and elasticity the conductors at the time of erection will have to comply with the latest specification of the British Engineering Standards Association. Minimum values are as follows (see opposite page).

In calculating the factor of safety the actual breaking load is taken. It is assumed that the wires are covered with ice to a radial thickness of $\frac{1}{4}$ in. (for the higher pressures $\frac{1}{2}$ in.) and are simultaneously subjected to a wind of 50 m.p.h or 8 lbs. per sq. ft. of the projected area. Under these conditions and allowing for

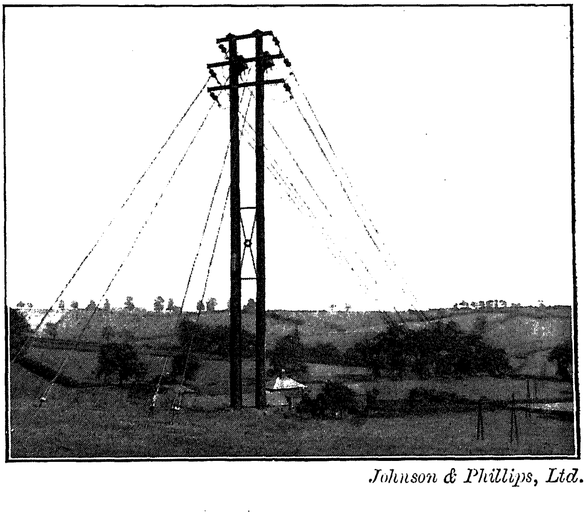


Johnson & Phillips, Ltd.

MEDIUM-VOLTAGE AND HIGH-VOLTAGE OVERHEAD POWER LINES.

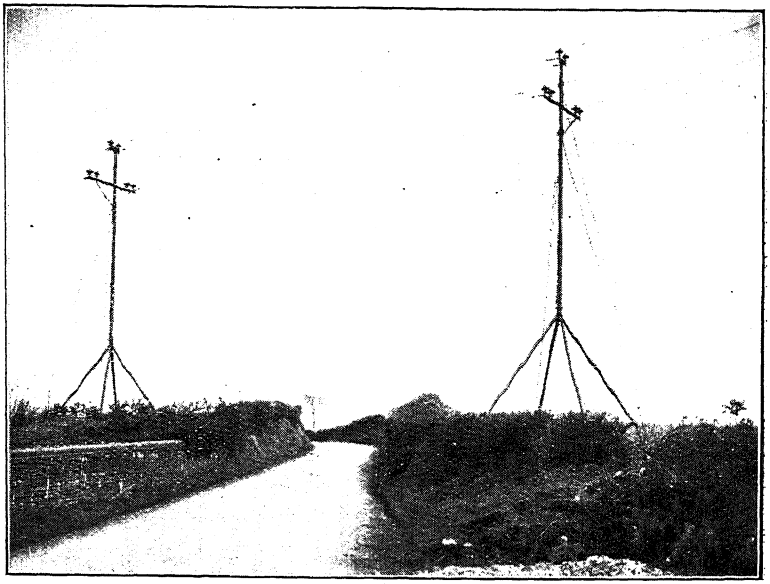
Current is supplied through 3 300 V overhead feeders and delivered, through pole-type transformers, to the 430 V overhead distributors. The copper conductors, ranging from 37 / 13 to 7 / 14 S.W.G. are carried by cantilever channel cross-arms, and are all single-circuit lines with a 7 / 14 S.W.G. earth wire below. The triangular spacing of the conductors is 2 ft. 6 ins. The creosoted wooden poles are A, H and single-type, 34 ft. long overall, from 7 in. to $8\frac{1}{2}$ in. diameter at 5 ft. from the butt, and at average spans of 50 yds.

A double-circuit, 3-phase, 11 000 V line running from a terminal pole to which current is conveyed by two 11 000 V underground cables; the cable cores are connected to the lines in the inverted pole-type trifurcating boxes. The conductors are of 1 S.W.G. copper spaced 4 ft. 4 ins. horizontally on the top and bottom cross arms and 5 ft. 4 ins. on the centre arm; below them is a 7 / 14 S.W.G. galvanised steel earth wire. The vertical spacing between conductors is 1 ft. 6 ins. The poles are 36 ft. long, $9\frac{1}{2}$ ins. dia. (at 5 ft. from butt); the span is 80 yds. and the minimum clearance from ground at maximum summer sag is 20 ft.



Johnson & Phillips, Ltd.

[*To face p.* 450.



Callender's Cable and Construction Co., Ltd.

A 33 000 V TRANSMISSION LINE ON 'KAY' POLES.

This type of pole is particularly suitable for cross-country transmission. It is preferably made of high-tensile steel tubes which may be painted or, better, wrapped with hessian impregnated with a bitumen compound. The foundations consist of buckled plates to which the tubes are bolted, and the connection between the four base tubes and the upright is made by a cast-iron block with five projections which slip into the appropriate tubes and require no bolt or other fastening. The ties are of galvanised steel rope. The foundation plate carries only the difference between the thrust of the tube and the pull of the wire, hence these poles can be used on marshy ground. They are easily transported and easily erected, and passage between the legs is not obstructed by bracing.

Material.	Elongation in 10 ins. %.	Breaking Load Tons per Sq. In.	Young's Modulus of Elasticity. Lbs. per Sq. In.
Copper . . .	1	27	18×10^6
Aluminium . .	4	11	10×10^6

the elasticity, the stress in the conductor at 22° F. (5·5° C.) must not exceed half the breaking load.

For the lower group of pressures no conductor may be used having a breaking load less than 650 lbs., equivalent to a copper wire weighing 200 lbs. per mile or an aluminium wire weighing 147 lbs. per mile.

The minimum computed height from the ground of any line conductor, at a temperature of 122° F. (50° C.), is fixed at 20 ft. as in the old rules. The conductors must not be accessible without a ladder or the like. In the case of the higher pressures, approved means for rendering a falling wire dead must be provided; and at all pressures above 250 V, D.C. or 125 V, A.C. approved means must be provided to prevent 'danger' from a falling wire. The conditions are somewhat more stringent along or across public roads or canals, or upon factory or other premises. Any auxiliary and earth wires or service lines are generally subject to similar restrictions. Lines crossing or near other overhead lines must be specially protected against accidental contacts, at the expense of the last comer.

Poles or supports (§ 323) of creosoted wood, iron, steel or reinforced concrete are permissible; for the higher pressures the supports must be consecutively numbered and must carry a 'danger' notice. The factors of safety allowed are 2½ for iron or steel and 3½ for wood or concrete under the same conditions as to ice and wind pressure as for wires. For lattice and other compound poles, such as A and H poles, special conditions of calculation are laid down. In the case of the higher pressures a continuous earth wire must be provided, connecting up all metal not alive,* and earthed at least four times in every mile; and the design must be such that the leakage on a contact occurring with live metal shall be at least double that required to operate the safety devices for rendering the line dead.*

Regular inspection and efficient maintenance is, as heretofore, insisted upon.

All materials used must, at the time of erection, conform with the latest specifications of the B.E.S.A. and with the Post Office Technical Instructions (No. XIII.) for the construction of aerial lines, as far as applicable.

No limiting span is laid down; it is clear that if the restrictions are complied with the distance between supports is immaterial. In certain cases the Regulations may be modified with the consent of the Electricity Commissioners. There are no detailed instructions (as found in the B.O.T. Regulations) for guarding against corrosion; but it must be guarded against both statutorily and as a matter of common sense.

In practice, it is seldom advisable to use conductors smaller than No. 5 or No. 6 S.W.G. Long spans are generally preferable in transmission lines, except where crossing streets or other places where the public have a right of way; there the span should be as

* The terms 'danger,' 'alive,' and 'dead' in their electrical sense are defined in the Regulations.

short as possible. It is good practice to duplicate each wire on transmission lines crossing roads; the two wires are then bound together, and the chance of breakage is reduced to a minimum. Earthing metal towers or other accessible supports is not always an easy matter in dry districts. A continuous earth wire (§ 347) is useful for the purpose. Cases have occurred where poles have been made 'alive' by leakage and have caused serious accidents to men and horses. During erection and repair, line wires should always be earthed. Neglect of this precaution has been responsible for cases of shock to linesmen from electrostatic charges on the line.

The Regulations require a liberal factor of safety (see above) in transmission conductors, and assume that a wind pressure of 8 lbs. (as against the B.O.T. 25 lbs.) per sq. ft. will be operative. Actually, such a pressure is rarely experienced at any distance from the coast, but provision must be made for abnormal conditions. The United States and Canadian recommendations allow a maximum stress of 30 000 lbs. per sq. in. for copper (14 000 lbs. for aluminium) at 0° F. with a ½-in. coating of ice and a wind pressure of 8 lbs. per sq. ft. projected area of conductor. In the Himalayas a stranded 7 / 10 S.W.G. cable has been observed when enlarged to 4 ins. diameter over a whole span.

Table 48, abstracted from Nystrom's, shows the relation between wind velocity and pressure.

The relation between the velocity, V ft. per sec., and the pressure, P lbs. per sq. ft., is given by $P = 0{\cdot}002\,29\ V^2$. If x be the angle of incidence of the direction of the wind with the plane of the surface, the effective value of P is $0{\cdot}002\,29\ V^2 \sin x$.

There are various ways of ensuring that a broken line wire is earthed before it reaches the ground. Where there is an earthed 'neutral' (as in 3-wire D.C. or 3-phase, 4-wire A.C. circuits) it may be split into two conductors carried below the other wires and cross-connected. A falling live wire must then strike the neutral and open the circuit-breaker. Alternative methods are to fix earthing brackets on, or immediately below, the wires at each end of each span; or to suspend a loop under the outers from the neutral at the top. Protection is just as necessary on overhead service lines; a man has been killed by touching the broken end of a service line attached to a house and apparently 'dead,' but actually 'alive' through a fan in the house, the fan being still connected to the unbroken service line.

TABLE 48.—*Velocity and Force of Wind.*

Mls. per Hour.	Ft. per Second.	Force in Lbs. per Sq. Ft.	Common Appellation.
1	1·47	0·005	Hardly perceptible.
2	2·93	0·020	Just perceptible.
4	5·87	0·079	Gentle pleasant wind.
8	11·75	0·315	Pleasant brisk gale.
16	23·45	1·25	
20	29·34	1·97	Very brisk.
25	36·67	3·07	
30	44·01	4·42	
35	51·34	6·03	High wind.
40	58·68	7·87	
45	66·01	9·96	
50	73·35	12·30	Very high.
55	80·7	14·90	
60	88·02	17·71	Storm.
65	95·4	20·85	
70	102·5	24·10	Great storm.
75	110·0	27·70	Hurricane.
80	117·36	31·49	
100	140·66	50	Tornado.

The safest arrangement where different sets of overhead lines have to cross (leaving trolley wires out of consideration) is to make the crossing at a support and at right angles. Guard brackets, earthed on the pole, can then be thrown out between the two sets. Even where all the lines belong to the same person, the not uncommon practice of running high and low-tension lines on the same supports should not be encouraged. Though it is obviously bad engineering, service lines or tappings are sometimes taken off aerial lines otherwise than at a point of support; this is prohibited.

325. Strength of Poles.—First consider the effect of wind pressure on the whole structure, on the basis of the old Board of Trade requirements. The general procedure illustrated by the examples in this and the succeeding paragraphs is the same whatever the regulations in the locality concerned; it is only necessary to substitute the appropriate loads, factors of safety, etc.

Wind pressure on *wires* $= 0{\cdot}6 \times (d/12) \times L \times n \times 25 = 1{\cdot}25dLn$ lbs., where d = diameter of wire in inches; L = length of span in feet; and n = number of wires. Denoting by H the

average height of wires above ground in feet, the moment (W) of wind pressure on the wires is given by $W = 1{\cdot}25\ dLnH$ lb.-ft., and is generally assumed to be operative on the pole 1 ft. above ground level.

The wind pressure on *pole* = $0{\cdot}6 \times$ (Mean diam. / 12) $\times$ Exposed height $\times$ 25 = $1{\cdot}25 \times$ Mean diam. in inches $\times$ Height in feet. The moment of this pressure, again assumed to be operative 1 ft. above ground level, is: P = [$1{\cdot}25 \times$ Mean diam. (ins.) $\times$ Height (ft.)] $\times$ Height / 2 = $0{\cdot}625 \times$ Mean diam. (ins.) $\times$ Height.[2] Then, allowing a factor of safety of 10 for wooden poles or 6 for steel poles, the poles must have a breaking stress not less than $10(W + P)$ or $6(W + P)$ respectively. The new Regulations will greatly reduce the actual strength required.

In the 3-phase transmission line worked out in § 302, there are three No. 3 S.W.G. wires, of 0·372 in. diameter. Assume that the ground permits spans of 500 ft., and that metal poles of 6 ins. average diameter are set with 30 ft. out of ground. Suppose also that a fourth No. 3 S.W.G. wire is used as continuous 'earth-wire' (§ 347). Then wind pressure on wires = $1{\cdot}25 \times 0{\cdot}372 \times 500 \times 4$ = 930 lbs., and if the average height of the wires be 28 ft. the moment of wind pressure = 930×28 = 26 000 lbs.-ft. = W. The wind pressure on pole = $1{\cdot}25 \times 6 \times 30$ = 225 lbs., and the moment of this pressure = $225 \times 30 / 2$ = 3 380 lbs.-ft. = P. The total bending moment to which the pole is subjected by wind pressure of 25 lbs. per sq. ft. = $W + P$ = 26 000 + 3 380 = 29 380 lbs.-ft., hence the pole (unless stayed all round) ought to have a breaking stress not less than $6 \times$ 29 380 or say 176 000 lbs.-ft., which is equivalent to 6 300 lbs. applied 28 ft. above ground level. Obviously no single pole of the assumed dimensions would give the requisite strength, hence a lattice or built-up structure would be necessary. (It may be noted that the Hamilton poles used for telegraph work have the following breaking loads, *viz.* ABC, 1 250 lbs.-ft.; CDE, 3 600 lbs.-ft. For steel tramway poles *see* Chapter 35.)

326. Stays and Stay Wires.—Galvanised steel stranded wire is used for stays, and a breaking stress of about 30 tons per sq. in. may be assumed; but for special work it can be produced up to 100 tons per sq. in. Stays may be needed either to strengthen the line at angles or terminal points, or to bring up construction on straight lengths to the required strength where the poles are not strong enough. They also serve to prevent the wires blowing together in a wind. They should be fixed to the post, if possible, *above* the line wires or at the resultant point between them, not below. It is evidently better at an angle to fix a stay in each alignment, rather than one only, in the resultant direction. Again, stays should be carried well away from the pole, for a stay at right angles would be in the best possible position. Finally, the stay

wire must run straight to the anchor, with no angle at ground level; it is best to undercut the hole for the anchor and to cut a slot in the ground for the stay wire. Where a wash-out is liable to occur in heavy rain four stays are sometimes advisable, two across and two along the line, to limit the trouble in case of a breakage of the line.

Taking first the case of a *terminal* stay, assume as in the previous paragraph that a line of three No. 3 / 0 wires (breaking strain 6 100 lbs.) is terminated on a pole, and that the stay is to carry the load. If the wires have been erected to have a factor of safety of 5, the tension which three such wires will exert on a terminal post will be $3 \times 6\,100 / 5 = 3\,660$ lbs. The tension to be taken by the stay would then be $(3\,660 / \sin\theta)$, where θ is the angle which the stay makes with the post. Thus, if fixed at right angles, in continuation of the line wire, the tension is evidently 3 660 lbs.; at 45° it is 5 180 lbs.; at 30°, 7 320 lbs. If the factor of safety of the stay is 5, it should have a breaking load of 25 900 lbs. for 45° and 36 600 lbs. for 30°. Iron stay wire may be taken as having a breaking load in lbs. of about $3\frac{1}{2}$ times its weight per mile, so that the stranded wire used should be equal to 7 800 lbs. and 11 000 lbs. per mile in the two cases. For steel, one-third or less of these weights per mile would be sufficient, according to the material used. In this and the following instances the roughest calculation suffices; there is no necessity to ascertain the exact angles dealt with. The following values of the sine will be accurate enough :—

Angle	90°	75°	60°	45°	$37\frac{1}{2}$°	30°	$22\frac{1}{2}$°	15°	10°	5°
Value of sine	1	·96	·87	·71	·61	·5	·38	·26	·17	·08

In the case of an *angle* stay, the resultant load, R, caused by the wires (*i.e.* the *line* wires) on the post is: $R = 2T \sin(\theta / 2)$, where T is the tension of the wires and θ is the *supplement* of the angle contained by the line wires. Thus, suppose the three No. 3 / 0 wires all make a horizontal angle of 120°, where the line changes its direction at a certain angle pole, then θ is 60°. The tension of the three wires is, as before, 3 660 lbs., so $R = 2 \times 3\,660 \times \sin(60 / 2)$. As $\sin 30° = 0·5$ the resultant load at this angle is the working load on the wires or 3 660 lbs., so a single resultant stay will be of the same size as the terminal stay already worked out above.

For other angles in the line the weight per mile of the terminal stay as previously determined should be multiplied by the following factors:—

Angle of Wires at Angle Post.	Supplement.	Multiplier for Stay Wire.
90°	90°	1·4
120°	60°	1·0
140°	40°	0·68
150°	30°	0·52
160°	20°	0·35
170°	10°	0·17

These factors are of course equally applicable to any other line for which a terminal stay has been calculated. If a stay can be fixed in each alignment, instead of one in the resultant, each component may be of half the size of the single stay. The straining screws should not be weaker than the stay wires attached to

them. As the stay is connected to the 'earthed' pole it is sometimes advisable, especially in the hills, to insulate the accessible part of it by means of a tramway 'strain insulator.' The pole may of course accidentally become 'alive' through a fault on the line and a bad earth, but accidental contact with a live stay wire is much more probable.

327. Dip and Stress of Wires; Spacing.—As regards the wires, the old B.O.T. rules assumed that the dip would be such that the wire was subject to $\frac{1}{5}$ breaking stress *under the worst conditions.* This is in fact seldom the case, but the elasticity of the wire and the 'give' on the posts may counterbalance abnormal conditions to a considerable extent. Where snow is experienced the overall diameter of a wire may be increased up to 3 or even 4 ins.; but in many cases, as in Indian hill stations, a high wind does not accompany the conditions for 'binding' snow. In such cases, if the wire is strained so that it will be subject to $\frac{1}{5}$ breaking stress at the probable minimum temperature, snow may be disregarded; and where snow never falls a somewhat lower factor, or smaller dip, may be allowed.

Thus, to continue the example of 3-phase transmission from the preceding paragraph, the breaking stress of a No. 3 / 0 S.W.G. hard-drawn wire may be taken as 6 100 lbs., and to allow a factor of safety of 5 we must take a working stress, S, of 1 220 lbs. (*see* col. 6 of Table 44, § 307) at the minimum temperature expected. The span L being 500 ft. and the weight, w, of 1 ft. of wire being 0·42 lb., the dip or sag D is given by: $D = L^2 \times w / 8 \times S = 500 \times 500 \times 0{\cdot}42 / 8 \times 1\,220 = 10{\cdot}8$ ft.

Suppose the minimum temperature to have been taken as 22° F., and that a maximum temperature of 100° F. occurs. Then the new dip will be $\sqrt{[D^2 + L^2 (T \times \frac{3}{8}k)]}$, where T is the rise of temperature and k is the coefficient of expansion. For copper $k = 0{\cdot}000\,009\,6$ per 1° F. Hence dip at maximum temperature $= \sqrt{[(10{\cdot}8^2 + 500^2)(78 \times \frac{3}{8} \times 0{\cdot}000\,009\,6)]} = \sqrt{(116{\cdot}5 + 70{\cdot}5)} = 13{\cdot}7$ ft. If the lowest wire were placed 27 ft. above ground at the pole, the height in centre of span would then be only about $13\frac{1}{4}$ ft., so that, unless the ground dipped down, a longer pole would be necessary.

The distance of the wires apart, or spacing, is regulated by two main factors: (i) the pressure, (ii) the dip; the latter depends on the weight of conductor and the span, as explained above, and the length of span is in turn dependent on the nature of the country. It is purely a commercial question whether high towers and long spans are preferable to short posts and spans. It has been shown in § 302 that the power lost in the line by reactance is proportional to the distance apart of the wires, and in long lines this must not be lost sight of. Short spans at low pressure should have the wires at least 1 ft. 6 ins. apart, and the distance must be increased

ı the pressure and the dip. Up to 10 000 V, with short spans, 6 ins. is sufficient. In long spans the wires should be ar- red so that no two are in the same horizontal plane, because heir liability to blow together in a wind. For pressures 20 000 V, the *minimum* distance in inches should be + 0·001 25 × volts. A useful dip and stress table will be ıd in Glover's *Vade Mecum.* A case has been cited in rica where a heavy short-circuit, and the consequent repulsion to the excessive current, caused a pair of wires to separate er great tension, and to fly together when the circuit-breaker d.

t may be necessary to increase the spacing of wires to avoid na discharge, but it is more effective to increase the diameter ıe wires (§ 316).

28. Temperature Rise of Overhead Conductors.—The erature rise (which affects the sag, § 327) of a *solid* copper uctor in still air is given approximately by—

$$t = 19{\cdot}8\rho I^2 / (d^3 \times 10^6);$$

re t = temperature rise, in °C.; ρ = specific resistance of -drawn copper, in microhms per cm. cube (§ 62), at tempera- $(t + t_a)$°C.; t_a = air temperature, in °C.; I = current, in eres; d = diameter of conductor, in inches (Table 44, § 307). l t is known the appropriate value of ρ cannot be determined, e it is necessary to assume a limiting temperature $(t + t_a)$, late t from the formula, and repeat the calculation with a rent assumed limiting temperature if the difference between atter and the temperature rise is not approximately equal to ctual air temperature.

he inverted formula $I = \sqrt{(td^3 \times 10^6 / 19{\cdot}8\rho)}$ can be used tly to determine the current corresponding to a specified erature rise above stated atmospheric temperature. For *nded* conductors the diameter of the solid wire of equal copper on should be taken for d in the above formulæ; the current tated temperature rise will be about 8 °/ₒ greater than thus mined from the formula.

n *steel-cored* and *aluminium* cables the temperature rise is than in copper conductors of equal resistance because the ting surface is greater.

n practice the size of conductors used in an overhead line is

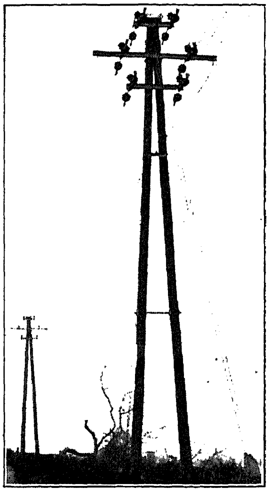
generally determined by considerations of power or voltage drop and not by temperature rise.

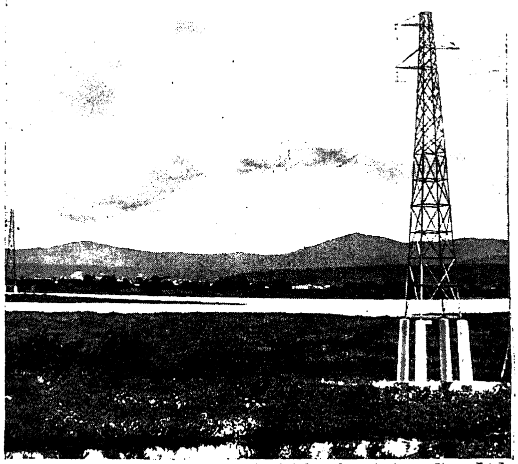
329. Long Spans in Transmission Line.—Where practicable long spans, supported on built-up towers, are preferable to short ones on ordinary poles, for high-pressure transmission lines; for every support is a potential source of trouble and every insulator of leakage. Where the ground is level the dip renders it necessary to have very tall masts, but in hilly country it is often possible to use Nature's supports and to run from spur to spur; in such cases the amount of the dip is hardly limited. If the wires in an exceptionally long span are run vertically one below the other there is no danger of them blowing together and short-circuiting the line.

For example, consider a span of 2 000 ft. consisting of three No. 3 / 0 S.W.G. wires. In calculating a 500-ft. span in § 327 the effect of wind pressure in increasing the stress was neglected; this must now be taken into account, so in the formula $D = L^2 \times w / 8 \times S$ (§ 327) the factor w will now be $\sqrt{(W^2 + P^2)}$, where W is the weight of the wire in lbs. per ft., and $P = (0{\cdot}05 \times \text{Wind pressure in lbs. per sq. ft.} \times \text{Diam. of wire in ins.})$. Then the equivalent $w = \sqrt{[0{\cdot}42^2 + (0{\cdot}05 \times 25 \times 0{\cdot}375)^2]} = \sqrt{(0{\cdot}176 + 0{\cdot}216)} = 0{\cdot}626$ lb. per ft. The dip, with a factor of safety of 5 at minimum temperature and 25 lbs. wind pressure, will then be $(2\,000 \times 2\,000 \times 0{\cdot}626) / (8 \times 1\,220) = 256$ ft.; or, with a factor of safety of 4, 206 ft.; and with a factor of safety of only 3, the dip would still be 155 ft.

Obviously such spans on level ground would involve impracticably tall supports, except in such cases as a river crossing, where the alternative would be an under-water cable (§ 292); instances, however, may be seen at Buffalo and elsewhere in the U.S.A., the tension on the wires being regulated by a pulley and weight inside the steel pole structure. In crossing a valley, on the other hand, these dips would be no obstacle, and the extra height gained under the wires by lowering the factor of safety would offer no advantage. The extra dip at the maximum temperature will not seriously affect the problem in the case of long spans—*see* formula in § 327. If on such a span silicon bronze wire of the same size, with a breaking stress of 110 000 lbs. per sq. in., were used instead of copper, the dip would be reduced to about half the figure given above; and in the case of only a few isolated spans, the extra loss of pressure could be ignored (*see* Table 49, in § 331).

330. Insulators.—Porcelain insulators are used for the most part, though glazed stoneware and glass are also extensively used in some countries. For low-tension work the insulators differ





British Aluminium Co., Ltd.

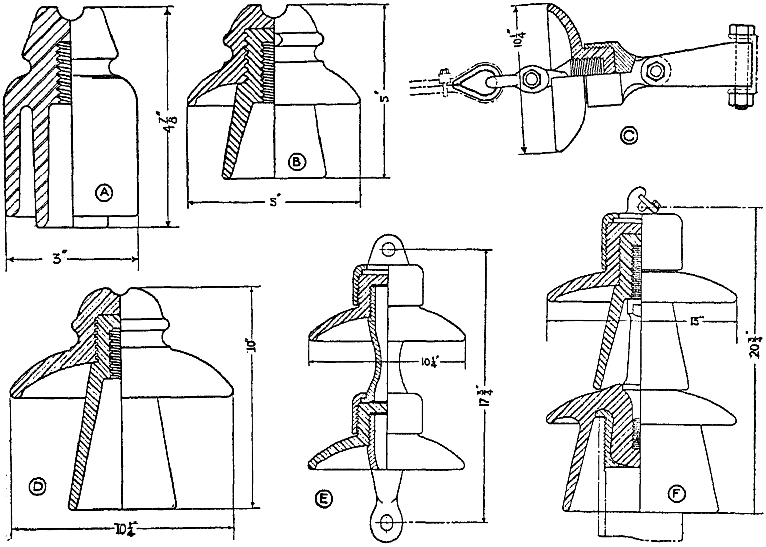
ALUMINIUM CONDUCTORS ON WOOD POLES.

A 6 000 V, 3-phase, double-circuit transmission line on A type poles. For equal conductance the aluminium is 20 to 25 °/₀ cheaper than copper. The diameter of the conductors is 28 °/₀ greater and the strength 18 °/₀ less than with copper, but this is of little importance on spans up to 200 ft. Little difference is involved in the height or strength of poles required.

STEEL-CORED ALUMINIUM CONDUCTORS ON STEEL TOWERS.

A 154 000 V, 3-phase, single-circuit transmission line with 1 100 ft. span. The aluminium wires are stranded round a core of steel wires, providing a cable which is stronger, lighter, and cheaper than copper cable of equal conductance. This makes possible long spans, reduces the number of towers and insulators, and thus increases the security of the line. The long spans permissible are particularly useful where a river or marshy ground has to be crossed.

[*To face p.* 458.



Typical 'Kalanite' Insulators for Power Transmission Lines.

(*By Callender's Cable & Construction Co., Ltd.*)

	Flash-over Test. Wet	Dry
(A) Low tension insulator . .	20 000 V	40 000 V
(B) 6 600 V straight line insulator	40 000 V	65 000 V
(C) 6 600 V end strain insulator .	40 000 V	65 000 V
(D) 33 000 V straight line insulator	85 000 V	120 000 V
(E) 33 000 V suspension insulator .	85 000 V	120 000 V
(F) 66 000 V straight line insulator	145 000 V	200 000 V

The lower petticoat of the insulator shown at (F) covers the cross arm and so reduces the liability to short-circuiting by birds.

[*To face p.* 459.

little from those used on telegraph lines, with double or triple petticoat, except that for large wires the mechanical strength must be greater. For high-tension circuits up to 50 000 V, or even 70 000 V, insulators of the same general type (*i.e.* pin supported) are used, but these are very much larger in order to secure mechanical strength sufficient to carry heavy lines and in order to increase the leakage path and the flash-over distance from the wire to the spindle and earth. For yet higher pressures, and up to 250 kV, suspension type insulators are used; these generally resemble inverted saucers or truncated cones, the under-surface being often corrugated, *i.e.* made with 'petticoats.' Such insulators are used mechanically and electrically in series to suspend the line from the cross-arm of the pole. The connection between successive insulators may be in the form of a pin cemented into the upper insulator which engages with a metal cap attached to the top of the insulator below ('cap' insulators); or the porcelain pieces may be formed with two tunnels at right angles through which pass stranded steel wire links providing the mechanical coupling between adjacent insulators (Hewlett insulators).

A number of typical insulators are illustrated opposite; these are made of 'Kalanite,' a proprietary hot-moulding (§ 75) insulating material which is much tougher than porcelain and consequently not subject to malicious damage by stone-throwing, etc. The dielectric strength of Kalanite is said to be equal to that of porcelain, but its resistance to the passage of A.C. is about 28 °/ₒ that of porcelain. The leakage current through a Kalanite insulator is about three and a half times as great as that through a porcelain insulator, but the actual amount of energy so dissipated is negligible in both cases at normal transmission frequency. The energy dissipated by the Kalanite, however, increases directly with frequency and, whereas vitreous insulators offer high resistance to the passage of high-frequency current, it is claimed that Kalanite permits lightning, switching, or other high-frequency surges to go safely to earth.

The characteristics and requirements of porcelain as an insulator are discussed in § 74, II(*c*), and the testing of insulators is mentioned in Chapter 40. The design and manufacture of insulators for extra high pressures are highly specialised problems in which great advances have been made during recent years. It is now recognised that the main problem of design is not to provide a leakage path of

maximum length on the surface of the insulator, but to shape and arrange the parts of the insulator, so that it and the surrounding air are subjected to as low, and as nearly uniform, potential stress as possible. A mechanical difficulty, where there are cemented joints between steel and porcelain, is to obtain secure fixing without risk of cracking by expansion or contraction stresses (the coefficients of expansion of steel and cement are higher than that of porcelain).

C. E. Elder (*Jour. I.E.E.*, Vol. 52, p. 304) recommends that pin type insulators should be secured to their pins by hemp twine packing, without any cement; the pin should have a rough-cut thread to grip the twine, and the latter should be of such size that only one layer is required; also, the twine should be spun loosely enough to bed well into the threads, and a felt wad should be inserted at the bottom of the hole.

A string of Hewlett insulators consists essentially of a chain of steel links insulated from each other by spacing pieces of porcelain; the mechanical strength of the suspension is unaffected by breakage of the porcelain, and there is little risk of the metal links being melted by arcing.

The use of cement in cap-type suspension insulators can be avoided by screwing the pin into a specially shaped nut which is held inside the insulator by a piece of porcelain of spherical form; the latter is inserted in the cavity before the insulator is baked and cannot subsequently be withdrawn (*see Sc. Abstr.*, B, 201, 1922).

The best modern pin-type insulators for high-pressure lines are designed with full recognition of the importance of securing uniformity in the electrostatic field, and these insulators are characterised by the absence of the very wide-spread hood which ormed a feature of older designs. The same principle is taken into onsideration in the design of suspension insulators. Where they re applicable pin-type insulators have the advantage that a shorter pole or tower can be used than with suspension insulators for the same clearance above ground.

At the pressures for which suspension insulators are used, and particularly above 100 kV, the uniformity or otherwise of the division of potential between the units of a string of insulators is an important factor. Even if only two insulators be used in series the P.D. across the one nearer the line is greater than that across the other, and, as the number of insulators in series is increased the departure from uniform division of potential becomes more marked.

With more than five insulators in series there is still from 20-30 % of the total voltage across the insulator nearest the line, and if this be a higher P.D. than one insulator can carry safely (as it may well be in the case of extra high pressure lines) we reach a limit beyond which it is impossible to insulate the line

addition of another insulator to the chain does not appreciably reduce ross the line-end unit. Fortunately, this difficulty can be overcome. ı of potential between the units of the string is determined by the gnitude of the capacity of the insulator itself and its capacity to earth. g the capacity of the line-end insulator, the P.D. across the latter can In this respect cap-type insulators are preferable to Hewlett insulators their greater capacity (say 30 $\mu\mu$F compared with 15 $\mu\mu$F.) In some ıp is extended by metallising the adjoining surface of the porcelain ıoop-spray or similar process), thus further increasing the capacity of or; the objection to this is that the end insulators are not standard, ore, involve extra cost and the risk of being used in the wrong position. cap insulators in series with Hewlett insulators offers another means of the capacity, and, therefore, the potential of the insulation as a whole. increasing the capacity of the end insulators the division of potential ualised by reducing the capacity of the links with regard to earth. be done by using oil-soaked hardwood or other insulating material ıetal links provided that sufficient mechanical strength can be obtained.

nerica a number of extra high pressure lines (up to 220 kV phases) are insulated by strings of standard suspension s, electrostatic flux shields being provided at each end of g. These consist of large metal rings, one earthed and one d to the line, placed concentric with the string of insulators, ing as electrodes between which is established a uniform ıtic field. The stress across the individual insulators is l by this means, and any flash-over or arcing occurs be- ıe guard rings, well away from the insulators.

flash-over voltage in fog or mist generally determines the of suspension insulators needed in a chain; the flash-over of the chain being satisfactory there is generally no risk of own by puncture.

ıe case of some three-part insulators mentioned by W. T. Taylor *E.E.*, Vol. 46, p. 538), the flash-over voltages for a single insulator and , 5, and 6 in series were, respectively: *Dry Test*—90, 160, 220, 274, 310, V. *Standard Precipitation Wet Test*—56, 90, 130, 175, 220, and 265 kV. ılators of this type in series are considered ample for a 60 000 V line, ısulators for a 104 000 V line.

lators should have the same mechanical factor of safety as es which they support (*i.e.* 5 according to the old B.O.T. Then the breaking load of a terminal insulator is the same of the wire with which it is used. Thus a No. 3/0 wire ıking load 6 100 lbs. and working load 1 220 lbs.; for a l insulator to carry this load, with a factor of safety of 5, *king* load should be not less than 6 100 lbs.

ere the wire is not terminated, but makes an angle or change

of direction at the insulator, sin $(\theta / 2)$ must not be greater than $(R / 2T)$. In the present case R, the permissible load on the insulator, with the required factor of safety, is 1 220 lbs.; T, the working load on the wire, is the same; so $R / 2T = 0{\cdot}5$. Therefore, when the wire makes an angle of 120°, the supplement θ being 60°, sin $(\theta / 2) = 0{\cdot}5$. As in the case of stays (§ 326), this angle is equivalent to a terminal point. At any more severe angle a stronger insulator is required; thus at 90°, where θ is also 90°, sin $(\theta / 2)$ is 0·71 and is greater than $(R / 2T)$, whereas at any less angle than 60° the insulator has a higher factor of safety than 5. Where a large solid copper wire makes a considerable angle, as at a corner pole, it is advisable to break up the angle by using two insulators; otherwise there is considerable danger of breakage occurring.

331. Conductors other than Copper. The use of aluminium as a material for overhead conductors has been mentioned in §§ 63, 308. The diameter of an aluminium wire is 28 % greater than that of a copper wire of equal conductivity, so the wind pressure and weight of snow are increased. According to the British Aluminium Co., the coefficient of linear expansion is 0·000 013 6 per 1° F., so the dip increases more rapidly than with copper (§ 327), and the spacing between wires must be greater. For long spans the difference in deflection between aluminium and copper wires may be so great as to require a higher pole or tower when the former metal is used. As greater care is necessary for stringing aluminium than copper wire, and also for its general andling, it costs more to erect. Mechanical connectors are often sed in place of soldered joints.

Cadmium-copper wires* offer the advantage of high tensile strength with relatively high conductivity.

For very long spans bronze and even steel (§ 309) wires are often used. Particulars of the materials mentioned are given in Table 49.

As mentioned in §§ 64, 309 iron conductors may be used economically for the transmission of relatively small amounts of power at high voltage, as in rural electricity supply. A typical American installation uses No. 8 S.W.G. galvanised iron wires for the transmission of 95 kVA at 22 000 V, 3-phase ($2\frac{1}{2}$ A per phase)

* *See also* 'Copper-Cadmium Wire for Electrical Transmission,' by W. C. Smith, *El. World*, Vol. 79, p. 223.

TABLE 49.—*Constants of Aluminium, Cadmium-Copper, Bronze, and Steel Conductors* (*see also* §§ 307-309).

	Conductivity; Copper = 100.	Breaking Stress. Lbs. per Sq. In.	Weight of Equivalent Conductor; Copper = 100.	Coefficient of Expansion per 1° F.	Percentage Increase in Resistance per 1° F.
Copper, hard drawn	100	56 000	100	0·000 009 6	0·238
Cadmium-copper (0·7 % Cd)	93·5	73 000	107	—	—
„ „ (1·1 % Cd)	90	100 000	111	—	—
Silicon bronze (1)	97	63 000	103	0·000 01	0·1
„ „ (2)	80	76 000	125		
„ „ (3)	45	110 000	222		
Phosphor bronze	26	101 000	384		
High carbon steel	11	125 000	910	0·000 006	0·2
Aluminium	61	30 000	48	0·000 011	0·217

for a distance of 31 mls.; the power loss in the line is about 9 %. The charging current of lines of these physical dimensions (whether of iron or copper) is a serious factor, and it is advantageous to secure induction motor loads along the line, as well as at the end, if possible (§ 158). Line loss is a minimum when the current at the load end has a lagging component about equal to half the charging current (*El. World*, Vol. 70, pp. 715, 1 252).

332. Cost of Overhead Lines.—It is impracticable to give much guidance as to the cost of transmission lines, underground or overhead. For underground cables a quotation should be obtained from the makers, and the cost of trenching and laying added. In the case of overhead lines the price of bare copper wire fluctuates between about £60 and £85 per ton in normal times. Ordinary

TABLE 50.—*Cost of Overhead Lines* (*Pre-War Basis*).

Size of Wire. S.W.G. (or Equivalent).	System.	Approximate Total Cost per Ml. Run of Line Erected. £.
7/0	2-wire	620 to 730
	3-phase	810 to 1 020
3/0	2-wire	440 to 550
	3-phase	590 to 730
1/0	2-wire	330 to 405
	3-phase	440 to 550
5	2-wire	205 to 260
	3-phase	295 to 405

light metal poles cost from £3 to £12 or more, and built-up towers for long spans may cost ten times as much. As a rough guide some figures for a few sizes of wire may be given, based on copper at £75 a ton, and lines of the strength required by the rules (for maintenance *see* Chapter 39).

333. **Economical Section of Conductor; Kelvin's Law.**— In the majority of actual cases a certain percentage loss of the delivered power is assumed from experience, and the pressure of transmission is settled according to the length of the line. Strictly speaking, these factors should be ascertained by the application of Kelvin's Law,* so that the annual cost of wasted energy in the line (C^2R watts) *plus* the annual allowance for interest and depreciation of the line shall be a minimum.

Thus, take the case of D.C. transmission calculated in § 296. The full-load current was 159 A. The probable load factor in any case can be approximately gauged from other working undertakings; assume it to be 31 %, and the *average* current will then be 50 A. Take the resistance per mile of any wire of about the size required, say 0·25 Ω per ml.; then for a mile of line (lead and return) the resistance is 0·5 Ω. The power lost in this would (on the average) be ($50^2 \times 0{\cdot}5 / 1\,000$) or 1·25 kW, equivalent to 11 000 kWh per annum per mile of *line*. From the rough estimates the probable output of the station in units and the total annual cost of the plant [interest, depreciation, fuel (if any), and establishment] will be known, giving the cost of each unit generated. In this case take the cost per unit as 0·66d., a fair figure for water power on the assumed conditions. Then the cost of the 11 000 units lost in transmission per mile would be £30 5s. Now lay out a diagram (Fig. 54) with resistance (inversely proportional to cross-sectional area) of copper horizontally and cost vertically, and mark the point where £30 5s. and 0·25 Ω per ml. meet. Draw a straight line through this from the origin. Next take any three sizes of wire somewhere near the mark and find the approximate cost of a mile run, *i.e.* in this case 2 mls. of wire. Taking this at £75 a ton, or say 8d. a lb., we get the following:—

7/0 S.W.G.	Weight of 2 mls. = 8 000 lbs.	Cost = £266
5/0 ,,	,, ,, = 6 000 ,,	,, = £200
3/0 ,,	,, ,, = 4 400 ,,	,, = £147

Taking 10 % of these costs for the charges on the line, mark off the points where these annual costs correspond with the ohms per mile of the wire thus:—

7/0 S.W.G.	Ohms per mile = 0·22.	Annual cost = £26 12s.
5/0 ,,	,, ,, = 0·29.	,, ,, = £20
3/0 ,,	,, ,, = 0·39.	,, ,, = £14 14s.

* Lord Kelvin's original statement was: 'The economical cross-sectional area is that for which the annual cost of energy lost just equals the annual interest on the capital invested.' Hopkinson's modification (which is particularly applicable to feeders for public electricity supply) provides for the ratio, of the gross annual revenue derived from the conductor to the total gross annual expenditure on it and on the energy supplied through it, to be at the maximum.

Draw the curve through these three points, and where this curve is intersected by the straight line the combined costs will be a minimum. The resistance per mile corresponding to this point, *viz.* 0·22 Ω per ml., will give the most economical size of wire to use.

In the case of 3-phase lines, the same data may be more easily obtained and plotted for a single conductor than for the three wires.

In the case of overhead lines results near enough for practical purposes will be obtained by considering the annual charges on the copper alone, though strictly speaking the cost should be increased for large sizes owing to the greater cost of the poles.

In the case of insulated cables the total cost should be used as a basis for the calculation, instead of the cost of the copper alone.

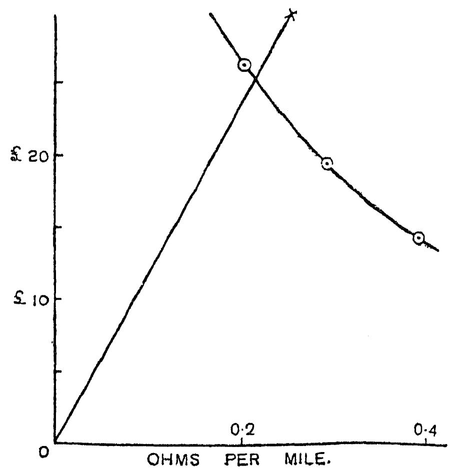


FIG. 54.—Graphical example of Kelvin's Law.

At 20 kV working pressure, the commercial considerations entailing the selection of such a voltage also determine to some extent the size of cable most commercially economical from the transmission and distribution point of view. In the case of distribution to a number of areas in various stages of development, the most economical section will be 0·1 to 0·15 sq. in. at 20 kV. Where a large amount of power has to be transmitted from a generating station to a main distributing centre, and the cable will be more or less fully loaded, it may be best to use, say, a 0·25 sq. in. cable, working at 33 kV. The considerations then to be taken into account are: (*a*) the limit of current density fixed by working temperature and largely dependent on method of laying and number of cables in proximity to one another; (*b*) the broad aspect of the whole scheme in which cable considerations are simply an item (C. J. Beaver).

It is evident that where water power is in question the generating cost per unit will usually be lower than with steam; if, however,

the available power is limited, and can all be sold, every unit lost in the line is a direct loss of revenue to the undertaking at the actual rate of sale, and the average *selling* price per unit should then be taken instead of the prime cost.

334. Cables *v.* Overhead Lines.—Underground cables are much more expensive to install than overhead lines, but in crowded cities the former are preferable if the undertaking can stand the cost. In this country, distribution circuits in towns are cabled with few exceptions (Chapter 24), but overhead work is often used to begin with, and cable substituted later on when the demand can be gauged accurately. Feeders or lines which do not require to be tapped *en route* (except long transmission lines) should as far as possible be placed underground; distribution lines, on the other hand, are more conveniently run overhead, as the cost of service lines is much less. This is an important point with a new undertaking; where houses are far apart, as in rural districts and colonial cities, the number of services per mile is abnormally low, so the cost has to be kept down if any profit is to be made. For long-distance transmission, aerial lines are universal.

Some idea of the relative cost of underground and overhead transmission lines is to be obtained from the following figures (pre-war), but these may only be taken as a general guide, since conditions differ enormously in individual cases, and even 1d. per kW per mile means £12 500 when the transmission of 30 000 kW, a distance of 100 mls., is in question. A.C. can hardly be transmitted underground at pressures exceeding 33 000 V, owing to the magnitude of capacity currents (§§ 288, 311).

Kilowatts . . .		200	500	1 250	10 000 to 15 000	30 000
Voltage		6 to 10 kV	6 to 10 kV	10 to 12 kV	50 to 100 kV	100 kV
Capital cost per kW per ml.	Overhead .	35s.-20s.	20s.-10s.	12s.-6s.	3s.-1s. 6d.	1s.
	Underground	75s.-50s.	40s.-25s.	22s.-15s.	3s. 6d.-2s.	1s. 6d.

In comparing the costs of transmission by 3-phase A.C. and by the Thury D.C. series system (§ 317), J. S. Highfield gives various estimates, from which the figures in table on opposite page are deduced.

The assumptions on which these (pre-war) figures are based are :—

Overhead.—6 wires for A.C., 4 for D.C. Line 100 mls. long; P.F. 0·85; full-load pressure drop, 10 %; lattice steel towers 150 yds. apart.

Underground.—Cables in stoneware ducts. Copper £62 per ton ; lead £13 9s.

Cost per kW per ml. of line or cable (erected) for transmitting		(a) 10 000 kW	(b) 30 000 kW
		s. d.	s. d.
Overhead—	(1) 60 kV, 3-phase	3 4	2 0
	(2) 60 kV, D.C.	2 8	1 5
	(3) 100 kV, 3-phase	2 6	1 1
	(4) 100 kV, D.C.	2 2	0 11
Underground—	(5) 20 kV, 3-phase	7 6	5 6
	(6) 50 kV, D.C.	3 6	—
	(7) 100 kV, D.C.	3 0	1 6

per ton. D.C. system, two wires equally insulated; sectional area—case 6 (*a*), 0·25 sq. in.; 7 (*a*) 0·125 sq. in.; 7 (*b*), 0·35 sq. in. A.C. system—case 5 (*a*), two 3-core cables 0·175 sq. in. area; case 5 (*b*), two 3-core cables 0·35 sq. in. area. Current density in cables 850 A per sq. in. Cost of trenching, laying, and two- or three-way conduit—cases 5 (*a*), 6, and 7, £834 per ml.; case 5 (*b*), £1 100 per ml. Further information relating to the cost of transmission is given §§ 332, 333.

At pressures for which they are applicable (§ 288) underground cables have the advantage of not being exposed to lighting, and of being out of the reach of most other extraneous causes of break-down. The security of supply is therefore greater with cables (where these are applicable) but when a break-down does occur it is more difficult and costly to locate and repair than is the corresponding break-down on an overhead line. Deterioration in cables can generally be detected before break-down occurs, but the nature of faults on overhead lines (breakage, short-circuit, etc.) is such that the occurrence is sudden. From the point of view of public safety and the safety of workmen cables have the advantage. The inductive drop is much greater in overhead lines than in cables (§ 310) but, on the other hand, the charging current is generally much greater in cables than in overhead lines (§§ 304, 311).

335. Telephones.—In every electric supply undertaking, and especially where there is transmission of power over a distance, telephone communication is necessary between the different substations and the power house. For this service overhead lines are almost invariably used. It is preferable to carry these circuits on a different alignment to the power wires, because when there is a fault in the transmission service interference is likely to result between it and the telephone circuits, and it is at such times

that clear speech is most important. In any case a double metallic circuit should be used, and not a single line with an earth return. The wires should be systematically transposed at frequent intervals, so as to neutralise the effects of induction due to variations in the current in the power line and also to the normal cyclic variation in an alternating current line; each 3-phase power circuit should also have two points, approximately dividing the total length evenly, at which the wires are altered in position 120°, so as to give one complete transposition in its length. In long lines several complete rotations or transpositions are allowed. It is necessary to safeguard the line against accidental contacts with the power circuit, whether due to breakage or to trees, and also to safeguard the operators against shocks from the line becoming charged inductively. In some cases it has been necessary, in order to prevent theft of wire, deliberately to charge the line to high pressure at night.

Although in very long lines the size of the telephone conductor becomes important, it is not so within the limits of transmission of power. Copper, phosphor bronze, mangan bronze, and silicon bronze wires are mostly used, and a wire of 100 lbs. per ml. (say No. 14 S.W.G.) is large enough electrically; a smaller size would be too liable to mechanical damage. For long spans copper wire is unsuitable, and these special bronzes have much greater tensile strength; but as the alloy and the strength are increased the conductance is decreased in a much greater proportion (*see* Table 49, § 331). The weight of a telephone wire may be taken without serious error from Table 40, § 280, according to its gauge or sectional area, whether it is copper or bronze. The cost of mangan bronze was normally about 1s 3d. to 1s 6d. per lb. pre-war, but varies with that of copper; phosphor bronze and silicon bronze are about 20 °/ₒ dearer.

A useful paper on telephone troubles in the tropics was read before the Institution of Electrical Engineers by W. L. Preece (*Jour. I.E.E.*, Vol. 53, p. 545). Amongst other points specially worthy of notice in India are the following: It is not uncommon for insects to find their way into a subscriber's instrument through the switch-hook; this should therefore carry a brass plate which keeps the slot in which the arm works entirely covered. There should be no terminals above the instrument, but the conductors should be taken through holes into the case and sealed up. Internal

wires should be separated as much as possible. Lightning protectors should be fixed where the wires enter the building, and not by the instrument; otherwise a fire may easily result. For the overhead line the use of glass insulators of the oil-filled type is suggested tentatively, as a protection against insects. As a protection from lightning troubles on the line, causing break-downs at the pole box, the use of the vacuum type of protector is recommended, in which two carbon blocks are inserted in an exhausted glass tube, the opposite surfaces being serrated and fixed about $\frac{1}{16}$ in. apart. A fuse in the circuit in addition is always essential. The use of an additional earthed iron wire, on the top of the poles, is also recommended (*see also* § 347).

336. Bibliography (*see* explanatory note, § 58).

OFFICIAL REGULATIONS.

Regulations prescribed by the Electricity Commissioners under No. A. 13 of the regulations for securing the safety of the public, made by the Board of Trade under the Electric Lighting Acts, 1882 to 1909. [There are two sets of these regulations, for pressures not exceeding and exceeding medium pressure D.C. and low pressure A.C.]

STANDARDISATION REPORTS, ETC.

B.E.S.A. Reports.

No. 55. Hard-Drawn Copper and Bronze Wire.

No. 65. Specification for Salt-Glazed Ware Pipes.

No. 128. Bare Annealed Copper Wire for Electrical Machinery and Apparatus.

No. 134. Specification for Steel Poles for Telegraph and Telephone Lines.

No. 137. Specification for Porcelain Insulators for Transmission Lines.

No. 139. Specification for Red Fir Wood Poles for Telegraph and Telephone Lines.

No. 144. Specification for Creosote for the Preservation of Timber.

BOOKS.

First Principles of the Electrical Transmission of Energy. W. M. Thornton (Pitman).

Theory of Electric Cables and Networks. A. Russell (Constable).

Electrical Design of Power Transmission Lines. W. T. Taylor and R. E. Neale (Chapman & Hall).

Overhead Transmission Lines and Distributing Circuits. F. Kapper (Constable).

Three-Phase Transmission. W. Brew (Crosby Lockwood).

Constant Voltage Transmission. H. B. Dwight (Wiley).

Overhead Electric Power Transmission. A. Still (McGraw-Hill).

Transmission Line Construction. R. A. Lundquist (McGraw-Hill).

Electrical Transmission and Distribution. J. R. Beard (Pitman).

Electric Power Systems. W. T. Taylor (Pitman).

Central Station Electricity Supply. A. Gay and C. H. Yeaman (Pitman).

Electric Mains and Distributing Systems. J. R. Dick and F. Fernie (Benn Bros.).

Standard Polyphase Apparatus and Systems. M. Oudin (Low).

PAPERS.

In addition to the references given in the text, the following deserve special mention: 'British Practice in the Construction of H.T. Overhead Transmission Lines,' B. Welbourn, *Jour. I.E.E.*, Vol. 52, p. 177; 'Design of High-Pressure Distribution Systems,' J. R. Beard, *ibid.*, Vol. 54, p. 125; 'The Distribution of Electricity,' W. B. Woodhouse, *ibid.*, Vol. 59, p. 85; 'Economic Aspects of Extra-High-Tension Distribution by Underground Cable,' R. O. Kapp, *ibid.*, Vol. 59, p. 94; 'An Electrical Review of E.H.P. Transmission,' R. Borlase Matthews, *El. Rev.*, Vol. 89, pp. 739, 796.

CHAPTER 15.

PROTECTION OF CIRCUITS AND APPARATUS.

337. Conditions against which Protection is Required. The two main functions of the systems and devices used to protect electrical circuits and apparatus are: (1) The prevention of damage wherever possible, and in other cases the restriction of damage, as regards extent and degree; (2) the maintenance of supply and operation in all parts of the system with the exception of the section directly affected by the fault. The principal irregularities which may cause damage to circuits or apparatus, and against which protection is therefore required, are: (*a*) Excessive current, due to overload or short circuit (*see* §§ 338-344). (*b*) Excessive pressure, due to switching surges, resonance or lightning (*see* §§ 345-351). (*c*) Failure of insulation, resulting in leakage to earth or between wires (*see* §§ 352-354). (*d*) Low voltage; or complete failure of supply, by loss of voltage at the generator, transformer, etc., feeding the circuit, or by interruption of the circuit (*see* § 355). (*e*) Reversal of current or power flow (*see* § 358). (*f*) Fire risk (§ 356). The causes and effects of these irregularities, and methods of protection, are discussed in the paragraphs stated. The need for protection has risen with the voltages and powers concerned in electricity supply systems and, though the total cost of protective gear is high, it is small in comparison with the value of the equipment protected and with the cost of the damage which might otherwise be occasioned.

338. Cause and Effect of Excessive Current: Short Circuit.—The power or 'load' in any electrical circuit is measured in watts or kilowatts (§§ 48-56) and is proportional to the product of pressure by current. The term 'overload' is, however, generally applied only to excessive current, partly because the standard system of transmission and distribution is the 'constant voltage' system (Chapter 20), and partly because an increase in voltage does not increase the heating of conductors (§ 49) but simply

increases the stress upon the insulation. The value of the current flowing in any circuit is determined by Ohm's Law (§§ 17, 44) provided that allowance be made for any back E.M.F. in the circuit (*e.g.* that of a motor or secondary cell), and that the impedance of the circuit (instead of its ohmic resistance) be considered in the case of alternating current. Thus, excessive current may result from the resistance between the supply mains being too low as, for example, when a low resistance motor is switched straight on to the mains, or when an excessive number of lamps or other current-consuming devices are connected in parallel between the mains. If the mains themselves or two parts of a winding, etc., at different potentials come into metallic contact or are bridged by a conductor (such as a spanner) of negligible resistance, the current becomes abnormally high (§ 339) and there is said to be a 'short circuit' between the points concerned. Short circuit is thus the extreme case of excessive current or overloading. In circuits where a back E.M.F. is normally operative, the reduction of this back E.M.F. is equivalent to a reduction in resistance or impedance and results in an increase of current. Thus, increasing the mechanical load on a motor results in a reduction of back E.M.F. (Chapter 28), hence the current flowing from the mains increases, and if the load on the motor be excessive, the current will also become excessive.

The principal dangers arising from excessive current are (i) overheating of the conductors; and (ii) the mechanical forces to which the latter are subjected.

Heating Effect.—The heat developed in a current-carrying conductor varies with I^2R (§ 49) and thus increases with the square of the current. The safe temperature limits for insulating materials have been discussed in § 80; the permissible currents in insulated wires for stated temperature are tabulated in § 280; and the heating of cables and overhead lines is discussed in §§ 291, 328. From these paragraphs there may be seen the effects of excessive current as regards temperature rise in ordinary circuit-conductors. In coiled windings the heating produced, particularly at the inner layers, is generally more serious owing to the low thermal conductivity and relatively small sectional area of the paths available for the dissipation of heat.

Mechanical Effect.—Every current-carrying conductor establishes round itself a magnetic field (§ 32) which, reacting with the

magnetic field round a neighbouring current-carrying conductor produces a mechanical force between the two—of attraction or repulsion, according to the directions of current flow. The left-hand diagram in Fig. 55 *a*, represents the individual fields round two parallel conductors (viewed in cross-section) which carry current in the same direction. It will be seen that these fields are opposed in the space between the conductors and cancel out more or less completely. The resultant lines of force are as indicated in the right-hand diagram (Fig. 55 *a*), and tend to draw the conductors together. On the other hand, if the currents in the conductors are in opposite directions, as in Fig. 55 *b*, the resultant field between the conductors is more intense than elsewhere, and

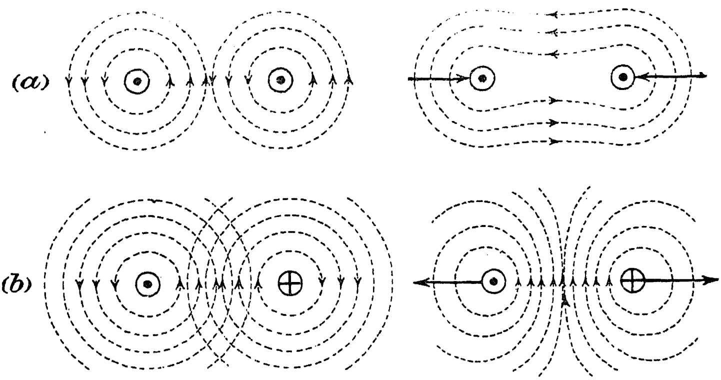


FIG. 55.—Attraction and repulsion between current-carrying conductors.

there is a crowding of the magnetic 'lines' which tends to force the conductors apart. The case represented in Fig. 55 *b* may be that of the lead and return of the same circuit, and it will be seen that the force between the conductors tends to open out the circuit so that it encloses maximum area (*see also* § 368).

The mechanical force of attraction (or repulsion) between two straight parallel conductors carrying a direct current of I amps. is given approximately by: $F = 0{\cdot}45I^2 \times 10^{-7} / a$; where F = force, in lbs. per in. run; and a = distance between centres of conductors, in inches. If the conductors carry alternating current the maximum value of the current, for the same effective value I, is $\sqrt{2}\, I$ (§ 30), hence the maximum value of the force between

the conductors is: $F_{max.} = 0{\cdot}9\, I^2 \times 10^{-7} / a$ lb. per in. run. Also the force oscillates between this maximum value and zero with twice the frequency of the A.C. supply, and is therefore much more likely to produce mechanical damage than is the sustained (and lower) force between two conductors carrying D.C. of the same effective value. According to L. B. W. Jolley (*Electrn.*, Vol. 85, p. 677), the *average* force between 3-phase bus bars mounted in one plane is given by: $F = 0{\cdot}338\, I^2 \times 10^{-7} / a$ lb. per in. run where I = R.M.S. amps.; and a = distance between centres of bars, in inches.

Examples (1) The steady force between two conductors, 3 ins. apart, carrying 2 000 A direct current, is: $F = 0{\cdot}45\, I^2 \times 10^{-7} / a = 0{\cdot}45 \times (2\,000)^2 \times 10^{-7} / 3 =$ 0·06 lb. / in. = about $\frac{3}{4}$ lb. per ft. run.

(2) The maximum value of the fluctuating force on two bus bars 6 ins. apart carrying 25 000 A alternating current (as at the first moment of a short circuit) is: $F = 0{\cdot}9 \times (25\,000)^2 \times 10^{-7} / 6 = 9{\cdot}37$ lb. / in., or 112 lb. / ft. run.

Under short-circuit conditions the force between current-carrying bus bars, generator-connecting cables, accumulator-connecting strips, etc., may be sufficient to cause deformation of the conductors and, possibly, breakage of insulators. The initial value of the short-circuit current is much greater than that of the steady or sustained short-circuit current (*see also* §§ 339, 370) and the instantaneous peak value of the current depends upon the point in the E.M.F. wave at which the short circuit occurs (§ 339). This instantaneous value of the current determines the maximum instantaneous force operative under short-circuit conditions; the formulæ in the preceding paragraphs apply only to steady D.C. or A.C. as the case may be.

Isolating switches (§ 362) may be opened by the force to which the blade is subjected under short-circuit conditions. Jolley (*loc. cit.*) gives formulæ for calculating the magnitude of this force under stated conditions; in the case of a switch 12 ins. between contacts the torque tending to open the switch when carrying 20 000 A ranges from 28 lb.-ft. with a blade 1 in. wide to $40\frac{1}{2}$ lb.-ft. with a blade $\frac{1}{4}$ in. wide. The total force distributed along the blade of a 300 A isolating switch, 10 ins. long, is about 100 lbs. when the current is 20 000 A, and 600 lbs. at 50 000 A. A bolt or latch is generally provided to prevent the switch from being opened by these forces.

In all the above cases it is assumed that the conductors are not

ɔn; if they be, the magnetic field produced by given current tly increased (§ 41) and the mechanical forces are corre-ıgly greater. There is no simple method of determining ıctance of the path followed by the leakage flux in such ɔut the experienced designer can estimate the probable n the end connections of generator windings, on transformer ıc., with sufficient accuracy to enable adequate mechanical t to be provided.* The forces developed in such cases ɪhort-circuit conditions are of the order of several tons, hence ıbstantial clamps are required to prevent movement of the gs which would abrade the insulation, or deformation which break the insulation or cause stationary and rotating parts

.ere D.C. generators or rotary converters are concerned bility to flashing over on overload (*i.e.* excessive sparking, ɔing into flashing between commutator bars and possibly n brushes) may impose a lower limit upon the permissible an do considerations of heating or mechanical stress.

. **Calculation of Short-circuit Current.**—Theoretically it ıple matter to calculate the current flowing in any case of ircuit by applying Ohm's Law (§§ 17, 44), but, in practice, tors concerned are variable and more or less indeterminate. simple case of, say, a 'dead short' (*i.e.* a direct connection ıppreciable resistance) between the conductors of a feeder at ; 1 ml. from a generator which is connected directly to the the current flowing is limited only by the impedance of the tor and that of the 2 mls. (lead and return) of cable. If ıssure drop in the generator and cable with normal full-load t I amps. be: $p = (IZ / E) \times 100$ %, where E = generator ə, and Z = impedance of generator and cable in ohms, we $Z = pE / 100\ I$, and if this be the only impedance in circuit ·eder short circuited at the far end), the short-circuit current $Z = 100\ I / p$ or $(100 / p) \times$ full-load current. Thus if a be 'shorted' at a point between the generator, and which is 5 % pressure drop on full load, the short-circuit current heoretically be $100 / 5 = 20$ times the full-load value. are, however, several factors to be considered. In the first

*ɘe also *Theory and Calculation of Electric Circuits*, La Cour and Bragstad ans); and *Principles of Transformer Design*, Still (Wiley).

place, the current so calculated may be greater than the short-circuit output of the generator (Chapter 40) which is naturally the heaviest current that can flow even with a short circuit at the generator terminals. Again, no heavier current can persist than corresponds to the maximum output of the prime mover (allowing for losses in the generator), though the stored energy of the moving parts will momentarily increase the output greatly. So far, it has been assumed that the generator voltage is fully maintained on short circuit, but this is far from being the case, even though automatic voltage regulators (§ 147) endeavour to maintain constant voltage. Further, it has been assumed that the reactance is known and constant, but, actually, it is very difficult to determine the exact value of reactance in a short-circuited system because this varies with the position of the fault, with the resistance of the fault itself, and with the saturation of all iron-cored windings in the circuit.

In the early days of A.C. engineering it was common to specify low internal reactance in alternators for the sake of close voltage regulation (§ 146), but it is now usual to provide greater reactance in order to limit the short-circuit current, dependance being placed upon automatic voltage regulators in order to maintain constant voltage under normal variations of load. Even with the higher internal reactance now employed, the short-circuit current may be 15 or 20 times the normal full-load current, but it quickly falls to, say, 2, 3 or 4 times full-load current owing to the generator voltage being greatly reduced by the reaction of the armature when carrying heavy current. Under short-circuit conditions the action of automatic voltage regulators obviously tends to increase the short-circuit current; to overcome this objection it can be arranged that the regulators automatically *reduce* the generator voltage when the main current exceeds a predetermined value.

It is the maximum instantaneous value of the short-circuit current which determines the maximum mechanical stress imposed upon windings, etc. (§ 338), and it says much for the construction of modern turbo-alternators that they will withstand dead short-circuit at full field excitation without mechanical injury. If the short-circuit current wave is initially asymmetrical (as it may be under the most unfavourable conditions) its amplitude may be about 1·8 times that of the initial short-circuit current under symmetrical conditions. An approximate formula for the maximum instan-

taneous value of the short-circuit current per phase under the most unfavourable (asymmetric) conditions is—

$$I_{max.} = 1{\cdot}8 \times E \times \sqrt{2} \,/\, Z = 2{\cdot}55\, E \,/\, Z;$$

where E = phase voltage; and Z = impedance per phase, in ohms. The duration of this severe current rush is very brief, and after a few cycles the current settles to its steady short-circuit value of 2-4 times full-load current. The actual value of the initial surge is a maximum if the short-circuit occurs when the E.M.F. wave is at its maximum; if the short occurs at some lower instantaneous value of E.M.F., the short-circuit current increases with the E.M.F. and prevents the latter from attaining its normal maximum value. The inductance of the path followed by the short-circuit current retards the increase of current from the normal to the short-circuit value and allows time for the E.M.F. to decrease somewhat. The thermal capacity of the conductors in the circuit allows them to carry the initial current rush without dangerous rise of temperature provided that the circuit be interrupted in a fraction of a second; even this brief delay permits the current to decrease (owing to the reduced E.M.F.), and greatly reduces the duty imposed upon the circuit breaker (§ 370).

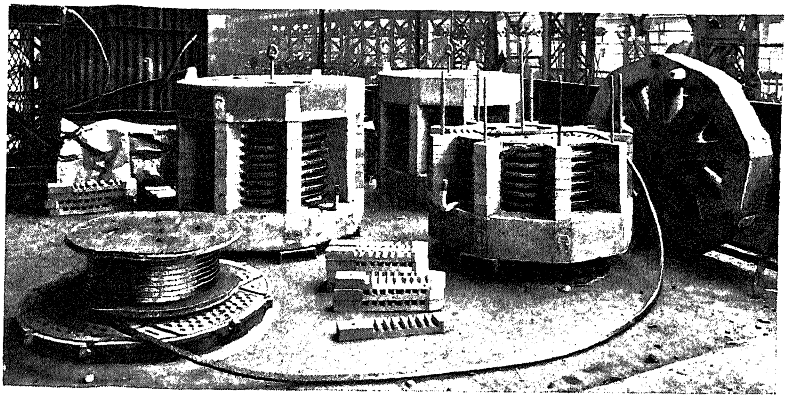
340. Limitation of Current; Protective Reactances.—The short-circuit current in any circuit may be reduced by increasing the reactance of the circuit, and this may be accomplished by connecting in series with the latter an inductive coil of wire (generally called a 'reactance coil'). The only loss of energy in this coil is the I^2R loss (§ 49) due to its ohmic resistance, plus the losses in its iron magnetic circuit (if any). The inductance of the coil reduces the power factor of the circuit (§§ 44, 45, 154), but does not involve dissipation of energy. As explained in the preceding paragraph, if the reactance causes p % voltage drop when carrying the normal full-load current of the circuit, the short-circuit current through the reactance—when the latter is connected directly to the full supply voltage—is $(100 \,/\, p)$ times full-load current. If it is desired to limit the maximum current of an alternator to 5 times full-load value, the total reactance (measured in terms of the percentage voltage drop which it produces with full-load current) must be $p = 100 \,/\, 5 = 20$ %, and if the alternator has 8 % reactance (as above defined), the external reactance required is 12 %

Reactances generally consist of large-section strip copper (or insulated cable) the ohmic resistance of which is so low as to cause negligible loss of energy. In air-core reactances the turns are separated and supported by porcelain, bricks, or concrete to secure insulation and to prevent deformation by mechanical forces on short circuit (§ 338). Iron-clad reactances (with iron magnetic circuits) are much smaller than air-core reactances for equal inductance, and they have the further advantage of being free from stray fields (which may affect instruments or induce eddy currents in steelwork near air-core reactances). On the other hand, iron magnetic circuits become saturated at much less than short-circuit current (unless the section of iron is very large), notwithstanding the use of air gaps in the circuit to increase the reluctance (§ 43); as a result the volt-ampere characteristic of iron-clad reactances is not linear whereas that of an air-core reactance is linear at all currents.

Generator reactances of from 10-20 °/$_{\circ}$ (on the voltage drop rating defined above) are commonly used in series with alternators to limit the magnitude of the short-circuit current. *Bus-bar reactances*, of from 25-50 °/$_{\circ}$, are connected between the sections of sub-divided bus bars so that, in the event of a 'short' on one length of bus bar the current which can flow to the fault from the other sections is limited; these reactances are traversed only by current flowing from bar to bar and not by the current delivered by one or several generators to a set of bars and flowing thence to feeders. *Feeder reactances*, connected in series with individual feeders, are of about 5 °/$_{\circ}$ (limiting the maximum current to 20 times full-load current), this relatively low reactance being adopted in order to reduce the voltage drop and the lowering of power factor.

Reactances cannot be used to reduce the maximum current to a non-injurious value; they simply reduce the peak value of the current thus reducing mechanical stresses (§ 338) and the power to be interrupted (§ 370). The actual interruption of the circuit pending the removal of the fault is effected by fuses (§ 342) or circuit breakers (§ 343).

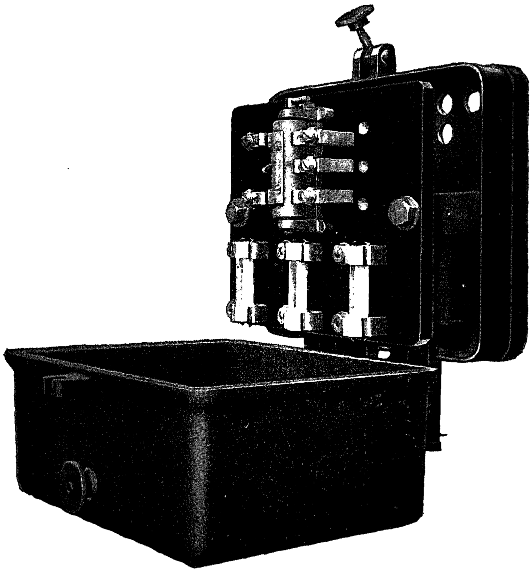
The reactance $2\pi fL$ of a coil (§ 44) varies with the product of frequency by inductance; the considerable reactance required in current-limiting reactances involves high inductance L, the frequency f of commercial supply being low. On the other hand,



General Electric Co., Ltd. (London).

PROTECTIVE REACTANCE COILS UNDER CONSTRUCTION.

These coils are designed to give 5 % reactance on a 11 000 V, 1 000 A, feeder circuit. The simplicity and strength of the construction are shown clearly. The stranded copper conductor is laid in the grooves of the moulded concrete arms, and the completed coil is practically indestructible.

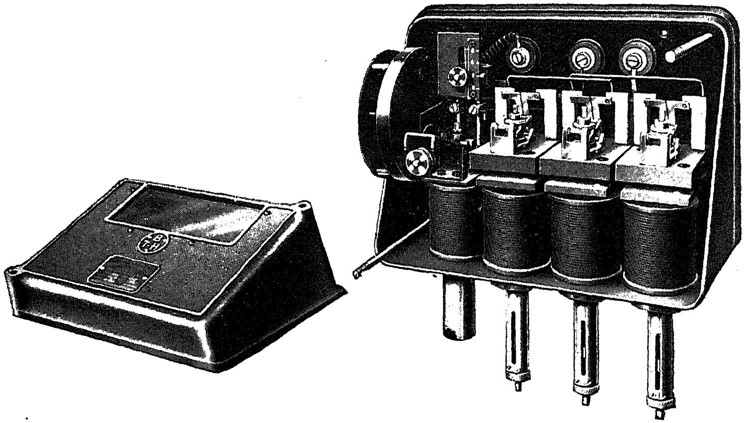


British Thomson-Houston Co., Ltd.

TRIPLE-POLE INSTANTANEOUS RELAY.

This type of relay can be used for overload and for leakage protection. A moving contact carried on a spring-actuated drum is normally held 'off' by a catch, which is tripped by the plungers being pulled up by the solenoids on a predetermined current being exceeded. The moving contact bridges fixed spring contacts in its 'on' and 'off' positions and may thus be used to break or make circuit, or for both purposes. It can be made to control two independent circuits. Current adjustment is by raising or lowering the plungers, and the movement of the drum is independent of the pull on the plungers. Delayed action can be obtained by shunting the trip coils with time-limit fuses.

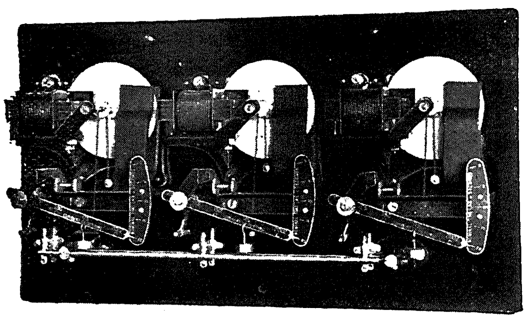
[To face p. 478.



British Thomson-Houston Co., Ltd.

DEFINITE TIME-LIMIT RELAY.

The equipment comprises three overload coils, and a time-element device, circuit-closing mechanism, and operating trip coil. When any one of the overload coils operates, the time element trip coil is energised, and the circuit closing mechanism commences to overcome the retarding effect of the time element. After a predetermined time, which is adjustable within wide limits, the secondary tripping circuit is closed. If required, one of the overload coils can be replaced by a sensitive coil, and the relay arranged to operate instantaneously on a small leakage fault whilst retaining the time limit characteristic for overloads.



Everett, Edgcumbe & Co., Ltd.

TRIPLE-POLE INDUCTION-TYPE OVERLOAD RELAY WITH INVERSE TIME LAG.

The movements are similar to those of the induction ammeter (Plate p. 114). The current and time settings are independently adjustable—the current by the position of the weight on the horizontal graduated beam, and the time by regulating the travel of that beam over a vertical scale. The contacts are of carbon and are seen at the bottom of the instrument. The time-current curves of all these relays are identical so that perfect discriminative protection is obtained.

[*To face p.* 479.

a very small inductance has a reactance high enough to obstruct the flow of high-frequency surges due to lightning, etc. (§§ 45, 346).

341. Interruption of Excessive Current.—The effects of excessive current may be utilised to obtain protection by making part of the circuit more sensitive than the rest to these effects, and arranging that the effects open the circuit (*i.e.* interrupt the current) at the selected point. Thus the heating effect of the current may melt a 'fuse' when the current exceeds a predetermined value; or the electromagnetic force developed by a solenoid may operate a mechanism which opens a switch in the circuit, either instantaneously or in accordance with a predetermined time element (§ 344).

342. Fusible Cut-outs; Fuses.—Fusible cut-outs, in which a fine and easily fusible wire or 'fuse' is connected in series with the circuit wires, are used in all domestic branch circuits and house services (Chapter 22). They are also used in industrial circuits, particularly for pressures up to 600 V and for (normal) currents up to 600 A; the cost of renewing heavy current fuses is a consideration and the rating of fuses (*i.e.* the current at which they melt) is less definite than that of switch-type circuit-breakers, hence the latter are generally employed in important circuits where an attendant is available to re-close the switch.

Tin or an alloy of low melting-point is generally used for fuses up to, say, 200 A normal current. The specific resistance of such metals is relatively high, hence the cross-sectional area required is much larger than that of copper fuses of the same rating. Copper fuses, for all but the heaviest currents, are inconveniently fine; they are easily damaged mechanically and by corrosion, with the result that they melt at less than the intended current. Whereas tin and similar fuses are not corroded seriously because their melting-point is low, copper fuses may often be at or near red-heat for considerable periods with the result that they are gradually oxidised.

The so-called 'Bimetal' fuse wire has important advantages. This consists of a copper wire, which would be fused at once by the current in the circuit it is designed to protect, sheathed with lead; the lead greatly increases the radiating surface, thus assisting in the rapid dissipation of the heat developed, and, having a greater cross-section than the copper, also carries some proportion of the current, despite its low conductance. Should the current rise

above normal the lead first melts off, and the fine copper wire (having to carry the whole current) then necessarily follows suit and breaks the circuit instantly. A fuse of this nature can carry some 80 % of its fusing current without danger of melting, whereas a copper fuse, under the like conditions, would be red-hot. The smallest size of bimetal fuse wire at present available carries about 6 A, so that for the smallest circuits a single strand of very fine copper or tin wire is generally used.

Table 51 shows the approximate fusing current of various sizes of copper, tin, and lead-tin (2Pb : 1Sn) alloy wires, the values given being calculated from Preece's formula: $I = a\sqrt{d^3}$; where I = fusing current, in amperes; d = diameter of wire, in inches; and a = 10 244 for copper; 1 642 for tin; and 1 318 for the lead-tin alloy. These figures are only approximations, as the length of the fuse, its direction (vertical or horizontal), the nature of the terminals holding it, the method of carrying it—whether in free air, on a porcelain bridge, or enclosed in a tube or cartridge—all affect the result. Enclosure in a tube filled with powder or submersion in oil (§ 375) naturally affect the rating of the fuse very materially by changing the facilities for the removal of heat. Table 51, is, however, a useful guide to suitable dimensions for well-ventilated fuses in air; if the fuse be mounted in a small asbestos tube, it may melt at half the current stated in the table. The resistance of a fuse causes a loss of pressure of from 0·1-0·5 V or more.

No matter how carefully an installation is fitted with fuses at first, there is always a danger that the occupier, after a fuse has melted or 'blown,' will replace it by a larger one in order to save trouble. By the use of standard non-interchangeable cartridge or screw-plug fuses, or by marking each fuse carrier with the current it is intended to carry and putting spare fuses alongside, something can be done to prevent this: but it is not unusual to find a piece of comparatively heavy iron or copper wire inserted where tin wire had been used originally. The protective value of the fuse is then illusory.

A certain amount of heat is required to raise a fuse wire to the melting-point, the amount being greater the heavier the fuse, the higher its specific heat, and the higher the melting-point. The rate at which heat is developed in the wire varies with I^2R, hence twice the current will bring the fuse to the melting-point in

TABLE 51.—*Fusing Current of Wires.*

Fusing Current. Amps.	Copper.		Tin.		Lead-tin (2 : 1) Alloy.	
	Diameter. In.	Approx. S.W.G.	Diameter. In.	Approx. S.W.G.	Diameter. In.	Approx. S.W.G.
1	0·002 1	47	0·007 2	36	0·008 3	35
3	0·004 4	41	0·014 9	28	0·017 3	26
5	0·006 2	38	0·021 0	25	0·024 3	23
10	0·009 8	33	0·033 4	21	0·038 6	19
15	0·012 9	30	0·043 7	19	0·050 6	18
20	0·015 6	28	0·052 9	17	0·061 3	16
25	0·018 1	26	0·061 4	16	0·071 1	15
30	0·020 5	25	0·069 4	15	0·080 3	14
50	0·028 8	22	0·097 5	13	0·112 9	11
70	0·036 0	20	0·122 0	11	0·141 3	9
100	0·045 7	18	0·154 7	8	0·179 3	7
150	0·059 8	17	0·202 9	6	0·234 8	4
200	0·072 5	15	0·245 8	3	0·284 5	2
250	0·084 1	14	0·285 1	2	0·330 1	0
300	0·095 0	13	0·322 0	0	0·372 8	3/0

(roughly) one-quarter the time; in other words, fuses have an inverse time element (§ 344), but owing to the uncertainty regarding the condition of the wire and its cooling facilities, it is not possible to utilise this time element to the same degree as with circuit breakers.

In circuits where the normal current does not exceed 10 A the fuses should interrupt the circuit before or when the current is three times the normal value; for working currents exceeding 10 A, the fuses should blow at or below twice the working current (*see also* I.E.E. Rules, Chapter 22). Fuses for high voltage circuits are mentioned in § 375.

A serious objection to the use of fuses in 3-phase circuits is the fact that the fuse in 1-phase may blow (due to its own deterioration or to an unbalanced fault in the system) leaving the fuses intact in the other two phases. This will leave the circuit alive beyond the fuses; also 3-phase apparatus may continue in operation on the two sound phases, the current in which may be high enough to damage the windings, but not high enough to blow the fuses. Automatic circuit breakers, opening all phases simultaneously, are therefore to be preferred in polyphase circuits.

Constructional details of fuses are described in § 375 ; and the installation of fuses is discussed in Chapter 22.

343. **Circuit-breakers.**—Any type of switch which is capable of interrupting safely (without sustained arcing or undue damage to contacts) the short-circuit current of a circuit may be termed a 'circuit-breaker' (§§ 365, 367). Such a switch is always arranged so that it can be operated by hand (either directly or by remote control, § 372) at the volition of the attendant, but it is also arranged so that it can be opened automatically by the action of a relay (§ 124) and trip coil. The switch is closed (by hand, electromagnetically, or otherwise) against the action of a powerful spring which tends to open the switch and is only prevented from doing so by a latch or trigger. This latch, when withdrawn by the movement of the plunger or core of a 'trip coil,' allows the switch to open instantaneously. The excitation of the trip coil solenoid may be effected by the main current, the coil then being connected in series with the switch, or it may be effected by current drawn from a storage battery or auxiliary D.C. bus bars in a local circuit which is closed by a relay. If the circuit-breaker is fitted with a series-connected trip coil it can be arranged that the tripping plunger is raised at any desired value of the current thus providing the circuit-breaker with automatic overload protection. Alternatively, if the trip coil be connected in shunt, across the supply leads, it can be arranged that so long as the supply voltage exceeds, say, 50 °/$_\circ$ of the normal value the latch of the switch remains closed, but directly the voltage falls below the predetermined minimum the latch is released (by the action of the trip coil) and the switch is opened; the switch has then automatic protection against low voltage, or a 'no-volt release.'

There would be obvious mechanical difficulties in arranging several trip coils (excited by different electrical connections) to operate a single release latch, but the same end can easily be attained electrically, by the use of relays. A relay consists essentially of an electromagnet the armature of which, when attracted to or released by the core of the magnet, closes an auxiliary electric circuit. Just as an electric bell can be rung by pressing any one of a number of 'pushes,' so can the trip coil circuit of a circuit-breaker be excited by the action of any one of a number of relays (*see* Fig. 59). If the respective relays be arranged to operate on overload, low-voltage, reverse power, etc., a

single circuit-breaker protects the circuit against all the contingencies covered by the relays. The relays are the controlling elements of the protection, and the protection which they afford is the automatic opening of the main circuit in the event of predetermined conditions arising.

Circuit-breakers can interrupt much greater power than fuses (§ 371), and they isolate the circuit completely, the switches in both poles or all the phases of the supply being coupled mechanically and opened simultaneously. Whereas a fuse provides only overload protection, a circuit-breaker and its relays can afford protection against all contingencies. Also, the setting of the various relays can be adjusted easily and accurately over a wide range.

The constructional features of circuit-breakers, trip coils, and

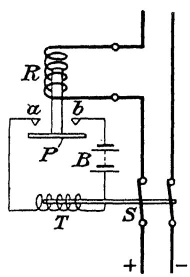


Fig. 56.—Instantaneous overload relay and trip coil.

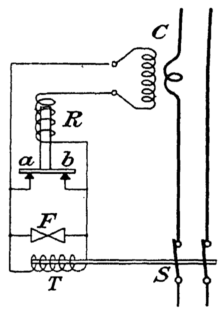


Fig. 57.—Overload relay with current transformer, and trip coil with fuse time element.

tripping mechanism are discussed in §§ 368, 372. Various types of relays are described in §§ 344, 355, 358, 359.

344. **Overload Relays; Time Element.**—The principle of the simplest type of overload relay is illustrated diagrammatically in Fig. 56. The relay coil *R* is in series with the circuit to be protected and, when the current therein exceeds a predetermined value, the plunger *P* is raised, short circuiting the contacts *ab* and closing the local circuit containing a battery *B* and trip coil *T*. The coil *T* being excited, its core trips the switch *S* and opens the main circuit. The coil *R* in the main circuit could be used as the actual tripping coil and is often so used in low or medium voltage, moderate current circuits where neither the size of the conductor

nor the insulation required makes it difficult to wind a suitable coil. For heavier current and/or higher voltage, the coil R is supplied from a current transformer (§ 108), as in Fig. 57, and the advantage of having a separate trip coil is that the relay can be delicate and sensitive whilst considerable power can be used to operate the trip coil; also, the latter can be actuated by any one of several relays (Fig. 59).

The overload relay on D.C. motor starters operates on the principle illustrated in Fig. 56, except that the contacts a, b are generally connected in parallel with the 'no-volt' or 'hold-on' coil instead of to a special tripping coil; then, when a, b are short-circuited by P, the hold-on coil loses its excitation and the starter handle is pulled to the 'off' position by a powerful spring.

In D.C. or single-phase A.C. circuits a single overload relay controlling a double-pole circuit breaker is sufficient, but in 3-phase A.C. circuits overload coils must be provided in two phases if the neutral is insulated and in all three phases if the neutral is earthed (§ 354); the circuit will then be opened no matter in which phase the excessive current flows.

The setting of overload relays can be varied so that the relay operates at any desired current between, say, normal full-load current and three times the latter.

The relay illustrated in Fig. 56 would cause the switch S to be opened *directly* the current exceeded a predetermined value and might thus involve unnecessary interruptions of working, for in many cases a momentary surge of current, far exceeding the permissible steady current, would not injure the circuit or apparatus. To allow for this, the relay may be furnished with a 'time element' which prevents the main switch from being tripped until the excessive current has been maintained for a predetermined time.

The time element may introduce a definite delay (say from 1-3 secs.) in the tripping, or the delay may be varied inversely with the main current ('inverse time element').

Instantaneous Relays are used in various protective systems (§ 359) to cause the main circuit to be opened directly some critical condition arises (*e.g.* lack of balance) which is a definite indication of a fault on the circuit protected.

Definite Time-limit Relays are used in a graded series on successive circuit breakers to prevent the whole length of a

feeder being shut down simultaneously. Thus, Fig. 58 represents a series of circuit breakers with overload relays R used on a feeder between a generating station G and substations S. If the relays R_1 be given a definite time element of 1 sec.; R_2, 2 secs.; and R_3, 3 secs., the relays will operate progressively from the far end of the feeder towards the station until the fault or overload is thus switched out. The object is to maintain supply in those sections which are nearer the generating station than the faulty section. To allow for the fact that a fault at X (which

FIG. 58.—Overload relays with graded definite time limits.

would be heavier than a corresponding fault in the more remote sections, § 339) is protected only by a relay with long time element, the relays may be arranged to operate with fixed time element up to a certain overload, and instantaneously at heavier overloads.

One method of arranging for a definite time element is indicated in Fig. 59. The trip coil A is connected, in series with a battery B, to bus bars C across which are connected the various relays, any one of which may bring about the opening of the main

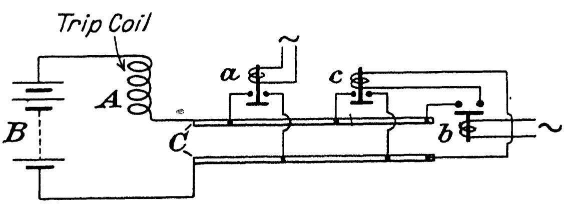


FIG. 59.—Various types of relays applied to trip coil.

switch. Thus, at a there is an instantaneous or inverse time element relay; and at b, c there is a definite time element combination, the instantaneous relay b (excited from the A.C. circuit to be protected) closing the circuit of the tripping relay c; until c closes, the current flowing through A is insufficient to operate the tripping mechanism. The definite delay in operation of the latter is determined by a pendulum and clockwork device, by the flow of mercury through a small orifice, or by other equivalent means.

Inverse Time Element Relays.—One method of securing a delay in action which decreases with the magnitude of the overload is to fit the plunger of an instantaneous relay (Fig. 56) with a dashpot; the timing of oil dashpots is, however, affected appreciably by temperature changes, which alter the viscosity of the oil. Another method is to use, instead of a solenoid and plunger, a small induction motor which winds up a cord carrying the contact-maker. The current at which the motor starts is varied by changing the weight on the cord, and the speed of the motor varies with the main current; hence the relay operates sooner the heavier the current. Yet another method is illustrated in Fig. 57. In this case, the relay *R* opens the contacts *ab* directly the main current exceeds a predetermined value. Current then flows through the fuse *F* and the trip coil *T* in parallel; mostly through *F* because of its lower resistance. After a time, which is shorter the heavier the current, the fuse *F* melts, and the whole current then passes through *T* and trips the switch. The weakness of this method is that the fuse *F* gradually deteriorates (§ 342) and may then cause the main switch to be opened unnecessarily.

Fixed or inverse time element relays are re-set automatically if the overload is removed before tripping occurs.

The setting of any type of relay is expressed as a percentage of the full-load conditions in the main circuit protected; if the relay is used with current or voltage transformers, the stated setting refers to the main circuit current or voltage.

(For reverse-power relays, *see* § 358.)

345. **Cause and Effect of Excessive Pressure.**—The whole or a part of an electric circuit may be subjected to abnormally high pressure (i) by a direct flash of lightning or by electrostatic induction from charged clouds (§ 346); (ii) by the sudden interruption of a highly inductive part of the circuit (§ 349); (iii) by sudden direct application of the normal voltage (§ 349); (iv) by resonance (§ 350); or (v) by the peculiar and unstable characteristics of arcs and sparks, particularly 'arcing grounds' (§ 351). Whatever its cause, the possible effects of excessive pressure are break-down of insulation and consequent danger to life and material (§ 352). Abnormal pressure would invariably lead to break-down were it not for the following facts: (*a*) The insulation of all properly designed circuits and apparatus is capable of withstanding a pressure much higher than the normal pressure

(Chapter 40), and in the case of extra high voltage systems the insulation is capable of withstanding indefinitely many of the pressure surges occurring in service. (*b*) A definite and considerable amount of energy is required to break down insulation so that if an abnormal pressure can be removed quickly enough the insulation will remain uninjured, though it would be broken down if the pressure were applied for a longer period (§ 72). (*c*) In many instances the abnormal voltage has a very high frequency of oscillation and will therefore take a path of high ohmic resistance (*e.g.* an air gap) in preference to the normal circuit which offers enormous impedance to the high-frequency current (§ 135 (1)).

If the cause of abnormal voltage cannot be avoided, the circuit must be safeguarded either by providing a suitable path of discharge for the excessive pressure, or by reinforcing the insulation of the circuit at the danger points, or by a combination of these methods.

346. Lightning Arresters.—The voltage of lightning may be inconceivably great, and a direct stroke will almost inevitably flash over the insulators and destroy the line at that point. Induced surges caused by lightning may, however, keep to the line, and affect apparatus in the power station or substation, or spark across an insulator and put the line to earth. Such surges, and some due to causes within the circuit itself, are of variable but always very high frequency, and will therefore take the least inductive, but not necessarily the best conducting, path to earth. Lightning arresters are designed to take advantage of this fact, and frequently consist of a spark gap, in one form or another, which the ordinary line voltage cannot break down, together with a carbon or other resistance in series. Should a high-pressure discharge cause an arc to strike across the gap, the line current will follow, but the series resistance limits the current and the arc dies down or is automatically extinguished, magnetically or otherwise. In order to ensure the discharge taking its allotted path, an inductive coil or 'kicking coil' (§ 45) is generally connected in series with the line itself on the station side of the arrester; the oscillating discharge is thereby forced to follow the alternative path. In some places in South Africa iron inductance coils have been used instead of the more usual copper coils, and have been found more effective.

Comb Arresters.—One end of a non-inductive resistance is connected to the line to be protected and the other end is connected to a 'comb' or serrated strip of metal, the teeth of which are set a short distance from those of a second comb. The latter is connected to earth. Lightning or other voltage surge breaks down the air gap between the combs, but a 'power discharge' (*i.e.* continued flow of current at the normal line voltage) is prevented by the high resistance in series with the gap. This type of arrester is suitable for line pressures up to 100 V direct current or 400 V alternating current.

Horn Arresters.—The general arrangement of a horn-type arrester is shown at (*a*) Fig. 60. The horns may be of copper or galvanised iron about ½ in. diam., and they are connected between line and earth in series with a high non-inductive resistance. High-frequency surges find it easier to break down the air gap and flow through the resistance *R* than to pass through the impedance of inductive apparatus in the generating station *G*. In order to oppose such an impedance to the high-frequency discharge outside the station coils *L* (of low reactance to low frequency current) are connected in the line on the station side of the arrester.

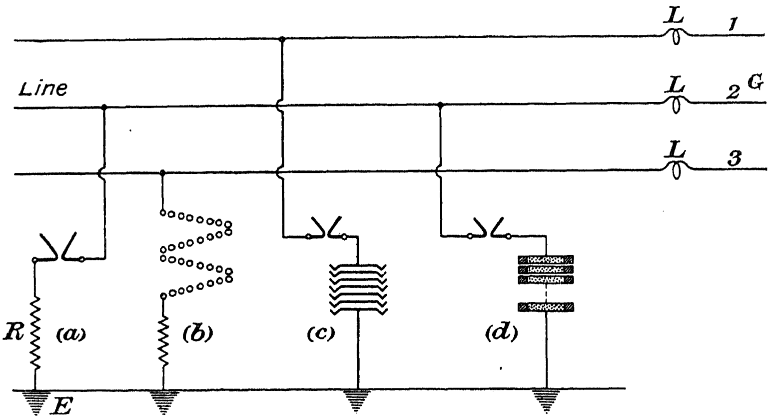


FIG. 60.—Various types of lightning arresters.

(Actually there would be only one arrester per phase, and the arresters on the three phases would be of the same type.)

When the gap between the horns is broken down by lightning the line current tends to establish an arc, but the magnitude of the line current is limited by the series resistance, and the arc runs up the horns until it breaks from extreme length. A useful setting is stated to be 1 mm. per 1000 V *plus* 1 mm. to prevent constant discharge.

The resistance *R* may be that of a water column in an insulating tube through the closed top of which is brought the connection from the horn arrester. When a discharge occurs some of the water is converted to steam and the remainder is driven down the tube into a surrounding tank. An arc is struck between the top electrode and the column of water, but as the latter continues to descend the discharge is soon interrupted. The steam then condenses and the arrester is re-set by the return of water from the outer tank.

The horn gap arrester is capable of dealing with heavy surges, but it can only operate on over-voltage and is useless on a low-voltage, high-frequency surge; if

the gap be set to protect the line against high frequency surges at a pressure only slightly exceeding the line voltage, dust, steam, insects, etc., may cause unnecessary break-downs. Horn-type arresters are used for line pressures up to 15 000 V (D.C. or A.C.), and for the protection of trolley wires (at 400-650 V, D.C.) two horn gaps may be used in series one being provided with a magnetic blow-out coil (§ 365) connected across a non-inductive resistance which is shunted across the second arrester; the magnetic blow-out comes into action in the event of sustained flow of D.C. across the gaps.

Impulse Protective Gaps.—In order to obtain protection against pressure surges of steep wave front (§ 349) without adopting an unduly small air gap (which would introduce risk of break-down at normal voltage), the ordinary horn-gap arrester may be provided with an intermediate electrode between which and the two horns there are connected impedances of different characteristics. It is arranged that, at line frequency, the impedances are proportional to the break-down voltages of the parts of the total gap across which they are shunted. At high frequency, however, the impedance of one of these shunts is much greater than that of the other; most of the high-frequency voltage is therefore imposed between the auxiliary electrode and one of the horns, with the result that this gap breaks down; the whole of the high-frequency voltage then comes upon the other gap which also breaks down. In effect there are two gaps in series, their total length being available as insulation against the line voltage, whereas practically the whole of a high-frequency voltage is placed immediately across a fraction of the total gap.

Multiple Gap Arresters consist of a series of cylinders, or truncated cones, with a short gap between each pair, the terminal elements connected to line and earth respectively (Fig. 60 *b*); sometimes the cylinders are connected in series with a high resistance, and in other cases some of the gaps are shunted by a resistance. The arc is broken either by the cooling effect of the metal or by the use of certain non-arcing metals—zinc, antimony, and bismuth. The number of gaps is generally about E / 800, where E = normal voltage between line and earth.

Water-jet Arrester.—In the jet arrester the line is connected straight to earth through a fine jet of water, the resistance of which is so high that the normal leakage is very small; the jet arrester provides a permanent leak to earth for high-frequency surges, irrespective of voltage; it is particularly useful for dispelling slowly accumulating static charges. In the case of low-tension D.C. installations a tank is substituted, and conducting plates within it are adjusted to allow a small continuous leakage from pole to pole, through the water, whenever there is a likelihood of lightning troubles. This type of arrester can only be used where there is a constant supply of water and no danger of freezing. Electrode-type electrically heated steam boilers (Chapter 26) afford excellent protection against over-voltage (the lines being earthed through the relatively low resistance of the water in the boiler), but these boilers are generally only in service during hours when there is surplus hydro-electric power available.

Electrolytic Lightning Arrester.—Sheet aluminium trays of V‾V-section (Fig. 60 *c*) are mounted one above the other with porcelain insulators between the rims of consecutive trays. The trough of each tray is filled with electrolyte similar to that used in electrolytic rectifiers, and the whole stack is placed in a steel tank which is then filled with insulating oil. The bottom tray is connected to earth and the top tray is connected to line. A film of aluminium hydroxide is formed upon the trays by electrolytic action, and the number of trays used is such

that the total resistance of the films is sufficient to withstand, say, 50 % higher than line voltage. Excess voltage (above about 350 V per cell) breaks down the films of hydroxide, but the latter reform directly the excess voltage has been dissipated and thus prevent the maintenance of a power discharge.

The stack of trays constitutes a condenser and—in order that there may not be a continual capacity current, and in order to prevent disintegration from continual leakage—it is necessary to use a horn gap in series with the arrester. Since the film on the trays gradually dissolves in the electrolyte it is necessary to re-charge the cell by short-circuiting the horn gap (through a suitable resistance) for a few seconds once a day; this is an inconvenience.

Oxide Film Arrester.—This arrester depends upon the fact that lead peroxide is a relatively good conductor whereas litharge (into which the peroxide is converted by heat) is an insulator. Capsules about 7 ins. dia. × ½ in. deep, consisting of metal discs fixed to a porcelain insulating and spacing ring, are filled with lead peroxide and stacked one above the other, the stack being connected in series with a horn gap arrester as in Fig. 60 *d*. The inside of the metal discs of the capsules is coated with insulating varnish, but when the voltage per capsule exceeds, say, 400 V the varnish is punctured and a discharge flows to earth. The heat developed (by I^2R) loss in the lead peroxide between the points of puncture converts the peroxide to litharge and thus seals the puncture and re-sets the arrester. The capsules generally remain in service for some years before the varnish films become covered with re-sealed punctures; when this stage is reached new capsules are required.

On 3-phase lines it is necessary to remember that if the arresters on all phases are connected to a common earth, and if there is insufficient damping resistance in circuit with each, the lines may be practically short circuited. With horn arresters this is not an uncommon mistake, and the arresters are blamed for the consequent trouble.

Moscicki condensers * are sometimes used to absorb high-frequency surges of any voltage; they will take care of rapid surges, have no permanent leak to earth, and can be installed where water is not available for jets. They are generally used in combination with Giles valves. Mechanically, they are rather fragile. They have been installed in various stations in Rhodesia and are fully considered in a paper by Wragg (*Trans. S. African I.E.E.*

---

* In these condensers a glass tube closed at one end is coated inside with silver (deposited chemically); the outer coating may be a similar layer of silver or the tube may be immersed in a conducting solution of glycerine and water contained in an outer vessel. By the use of a suitable thickness of glass and by avoiding sharp corners therein the condensers can be made to withstand high voltages. A Moscicki condenser described by W. M. Mordey (*Jour. I.E.E.*, Vol. 43, p. 621) consisted of eight tubes each 2 ins. dia. × 2 ft. 9 ins. long (3 ft. 2 ins. with connections); the condenser was intended for A.C. working at 10 000 V. and had a total capacity of 0·03 μF.

June, 1915). The use of condensers may increase the dangers arising from arcing grounds (§ 351).

Whereas a choking coil or inductance retards the growth of current and causes the applied E.M.F. to "pile up" on the end turns of the inductance to which it is applied (§ 349), a condenser has the opposite effect and tends to flatten the wave-front of the applied E.M.F. A system of protection which utilises these two phenomena and is applicable to English conditions consists in connecting a choke coil and a length of lead-sheathed cable in series between an overhead line and the generator or other apparatus in the power station or sub-station. The sheathing of the cable is connected to earth and so is the neutral point of the generator or other apparatus to be protected. The leading-in cable from each line may thus be regarded as a condenser connected in parallel with the corresponding phase of the generator, etc. The choking coil delays the increase of the current set up by the lightning or surge E.M.F. and this current charges the condenser (*i.e.* the cable) to a moderate voltage, much lower than that of the surge. The choking coil is sometimes omitted, reliance then being placed entirely upon the protective condenser-action of the cable. In either case the abnormal voltage on the line is dissipated partly by the ohmic loss experienced in surging to and fro on the line, and partly by flowing to earth through the cable-condenser.

347. Earth Wires.—A continuous steel earth-wire (often barbed) is generally run along the top of the poles of a transmission line, and serves to protect the conductors to some extent from lightning, by maintaining a zone at earth potential and by acting as a lightning conductor (§ 348). If underground cables are used to carry aerial lines across a street, as is sometimes the case, the overhead earth-wire should be brought down also, and wound on to the cable sheathing; and earth plates should be provided at each side of the crossing. The wire should in any case be earthed at every second or third pole if possible. Where no good natural earth can be found in which to bury the coil of earth-wire, an iron pipe is driven into the ground and either coke or salt filled in; it should be placed where rain will run in. The earth connection for all types of protective devices should be as short as possible to be effective, and especially for condensers. On a wood-pole line the use of an earth wire increases the risk of short circuiting by birds.

The Electricity Commissioners' Regulations concerning earth-wires are mentioned in § 324.

348. Lightning Conductors.—In order to secure absolute protection of buildings from lightning * a complete network of wires, connected with earth at many points, would be made to cover the whole structure; this is indeed practically done in the case of magazines. Ordinarily one or more lightning conductors are used, according to the size of the building, and the nearer the arrangement corresponds to a complete screen the better will the protection be. Iron or steel wire or stranded rope is considered to be more effective than copper, and is also less liable to be cut away and sold.

A conductor should run as directly as possible from its highest point to earth, not following the contour of the building but bridging over all projections. It should be so supported that there is no risk of its fracture by subsidence of the structure. As far as possible it should be run where it will not be within striking distance of metals on the inside of the walls, such as gas or water pipes or electric wiring, as there is always a danger of a discharge flashing over; insulators should not, however, be used as supports. It is good practice to connect together all the separate conductors on a building by horizontal ring conductors both on the roof and near the ground, and also to connect them electrically to any outside metal work, such as rain pipes, iron or lead roofing, ventilating pipes, and the like. There cannot be too many multiple vertical points or aigrettes; apart from the main vertical rods, short ones should be joined to the upper horizontal conductor at frequent intervals, and especially at all points above the general level. Lightning conductors sometimes terminate in a large corkscrew-like aigrette, of several spirals, apparently to improve their appearance; this acts as a powerful choking coil, and is probably worse than having no conductor at all, as a high-frequency discharge will almost certainly choose another path.

Joints in the conductor should be made both mechanically and by soldering, and the conductors should preferably be painted, even if already galvanised. For iron or steel conductors the best earth plate is a perforated pipe of the same metal, containing the end of the conductor packed round with granulated carbon, and placed where rain off the roof will keep it moist. Modern copper earth plates are often made of No. 16 gauge sheet metal with a number of triangular tongues or projections stamped out from the solid to form points from which the discharge may take place more readily. It is convenient to have disconnecting links arranged so that the resistance from one earth plate to another

* A very instructive address on this subject by A. Hands, is reported in *Electricity*, Vol. 30, pp. 126, 185, 191.

can be readily measured through the intervening ground. This varies enormously in different localities, but a comparatively high resistance is immaterial in a place where a really good natural earth can nowhere be found. Owing to electrolytic action between the earth plates and moist ground, D.C. tests of earth-plate resistance are somewhat inaccurate, though, by reversing direction after each test, results near enough are obtained; there are, however, methods of and apparatus for testing, using interrupted or alternating currents. The customary method of ascertaining the resistance x of an earth is by means of two other auxiliary or independent earths y and z. By means of the Wheatstone bridge (§ 120), readings (both direct and reversed) are taken of each pair in turn, deducting the resistance of the leads and recording the average value of each pair in ohms. Then if $(x + y) = p$; $(x + z) = q$; and $(y + z) = r$, it follows that $x = (p + q - r)/2$.

349. Switching Surges.—Abnormal stress may be placed upon the insulation of a circuit either when 'switching on' or when 'switching off.' On switching a transformer into circuit the voltage may rise to about twice its normal value unless it happens that the switch is closed at the instant when the voltage is a maximum and the magnetising current (lagging 90°) is therefore zero for the moment. If the switch be closed very slowly a flash-over will ultimately occur at the moment of maximum voltage; this avoids the voltage surge otherwise set up but it damages the switch contacts. In this and other cases the pressure surge on switching-in may be reduced by closing the circuit through a high resistance which is connected between charging contacts (§ 368) and the main switch contacts.

Apart from the possibly excessive value of the pressure surge when switching-in, there is a temporary concentration of stress on the end turns of inductive windings. At the moment of switching-on practically the whole applied pressure is concentrated on the end turns, the building-up of the current being delayed by the inductance of the winding. The steeper the wave-front of the applied pressure the more severe is this concentration of stress, and the only way to avoid break-down is to reinforce the insulation on the turns concerned or, alternatively, to connect a suitably insulated reactance in series with the winding. This reinforcement of insulation is required at both ends of a delta

winding, and at every tapping point if the tappings be at the line end of the winding.

On switching off or otherwise interrupting the circuit of an inductive winding (*e.g.* a motor field winding by returning the starter to 'off') there is a sudden collapse of the magnetic field which, in collapsing, induces an E.M.F. in the winding. This E.M.F. is higher, the greater the initial magnitude of the field and the more rapid its collapse. To protect the switchgear from the vicious arcing, and the insulation from the severe strain which otherwise arises, the inductive winding should be switched in parallel with a non-inductive resistance a moment before it is disconnected from the main circuit; there is thus provided a circuit in which the energy stored in the magnetic field (§ 57) may be dissipated harmlessly.

The violent fluctuations of load in electric arc furnaces, including frequent interruptions of circuit during the early stages of melting, impose severe stresses on the end turns of the transformers supplying the furnaces.

350. Resonance.—As explained in § 47 a circuit containing inductance and capacity in series may be in resonance, in which case the voltage across the inductance and across the capacity may be indefinitely high, however low the applied voltage. The resonant voltage is only limited by the ohmic resistance of the circuit, and may easily be high enough to break down the insulation of the circuit. The relation between inductance and capacity required to establish resonance varies with the frequency of the current (§ 47) and there is therefore especial danger of resonance: (i) If an excited alternator be run up to speed (or a motor or converter be allowed to slow down) whilst connected to a circuit, because the current then passes through all values of frequency below the normal value. (ii) If the pressure wave be not a pure sine wave, because resonance may then occur at the frequency of some of its harmonics. (iii) If the circuit be subjected to an earthing ground (§ 351), because the irregular currents then flowing contain many harmonics.

Since the amplitude of resonance decreases as the ohmic resistance increases, the temporary addition of resistance is a useful precaution where there is risk of resonance. The useful employment of resonance in half-wave and quarter-wave transmission is referred to in § 318.

351. Arcing Grounds: Intermittent Earths.—In a transmission system, the neutral point of which is earthed directly or through a resistance (§ 354), the current flowing through an earth fault on one phase to the earth connection of the neutral will be sufficient, ultimately if not at once, to operate the overload protection devices (§§ 342, 343) or the leakage or balance selective protective devices (§§ 357 *et seq.*). If, however, the system be operated with isolated (non-earthed) neutral the only effect of an earth fault on one phase of a 3-phase star-connected system will be to raise the potential of the sound phases to $\sqrt{3}\,E$ volts above earth, where E is the normal voltage between line and neutral. Such, at any rate, is the theory of the isolated-neutral system and if the earth connection on the faulty phase be a definite one, the new distribution of potential will be effected without much surging and will then remain steady; provided that the insulation of the sound phases can withstand the higher voltage to which it is subjected the system can remain in service until there is an opportunity to locate and remedy the fault. If, in the meantime, an earth fault occurs on one of the other phases as well there will be a short circuit between the two faulty phases.

One of the chief dangers of the isolated neutral system arises from the fact that an earth fault on one of the lines is rarely in the form of a definite connection to earth. It is almost invariably in the form of an arc which, being shunted by the capacity of the line to earth, is unstable. After the first extinction of the arc there is left on the line a relatively steady high-voltage charge which, added to the normal line voltage, causes the arc to be struck again. This action may be repeated indefinitely, exceedingly high voltages being built up by cumulative charging of the line, and surges being established which vary in frequency and amplitude according to the electrical constants (R, L, and C) of the circuit and the position of the 'arcing ground' in the system. Apart from the possibility of their establishing resonance (§ 350), arcing grounds subject the insulation of the line to abnormal voltages.

One method of suppressing arcing grounds consists in providing each line with an *arc suppressor*, *i.e.* an automatic device which, in the event of a break-down to earth, at once connects the line affected definitely to earth near the station. The line thus being rendered 'dead' the arc is extinguished, but the

definite earth connection involves considerable shock to the system, and by raising the voltage of the sound phases (as explained above) introduces a risk of break-down at some other point. It is generally arranged that the definite connection to earth is temporary, in the first instance, so that normal service may be resumed if the earth fault is cleared; if the fault persists the suppressor is locked 'in' the next time it closes.

An alternative method of protecting systems against arcing grounds consists in using the *Petersen earth coil* which is designed to neutralise the capacity effect of the line and, by removing the residual charge on the latter, to prevent the arc from being re-struck. The action of the coil may be explained as follows * :—

Referring, for simplicity, to a single-phase network, the phases 1, 2 (Fig. 61) have capacities C_1, C_2 with regard to earth; and the 'earthing coil' L is con-

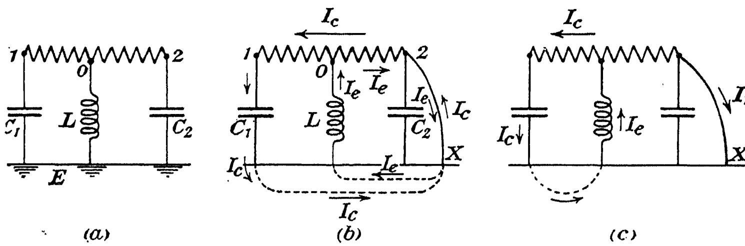


FIG. 61.—Illustrating the action of the Petersen earth coil.

nected between the neutral point O and earth. In the event of a fault ($2 - X$, Fig. 61 *b*) to earth on phase 2, the current I_e flowing to earth and back *via* L is, neglecting resistance: $I_e = E / 2\pi fL$ (§ 45), and lags 90° on the voltage E between phase conductor and neutral. The capacity earth current is the charging current, at voltage $2E$ of the capacity C_1 of the sound phase and is: $I_c = 2\pi fEC$ (§ 46); this current leads 90° with regard to E and is therefore in direct opposition to the current I_e. The paths of the currents I_e, I_c are shown by the arrows in Fig. 61. In order that I_e may equal I_c: $2\pi fL = 1 / (2\pi fC)$, *i.e.* the inductive reactance of the earth coil must equal the capacity reactance of the network capacities against earth. If this condition be fulfilled the currents I_e, I_c will cancel out in the fault $2 - X$, *i.e.* the earth fault current will be zero and the arc will be suppressed; without the coil L the capacity current of the sound phase would flow through the earth fault and cause intermittent arcing.

Actually the currents I_e, I_c have each a power component (due to the resistances, etc., of the circuits); these components do not cancel, but add together to form the resultant current I_r through the fault (Fig. 61 *c*). It is claimed that the residual earth current is very small (from 4-15 °/₀ of I_c), and that it is in-

* *See also Elekt. Zeits.*, Vol. 40, p. 5; Vol. 42, p. 695; and *Science Abstracts*, Vol. 22, B, No. 830; Vol. 25, B, No. 113.

capable of maintaining the arc; also, that effective protection is provided even when the inductive and capacity reactances are not balanced accurately, so that there is ± 30 % difference between I_e and I_c.

It is claimed that the Petersen coil is far more effective than a simple resistance or gap discharger between neutral and earth, in dispersing the dangerous charge on the faulty line, but opinions differ as to the kVA capacity of lines to which the system can safely be applied, and as to the possibility of dangerous pressures being established by resonance between the capacity of the lines and the inductance of the earthing coil. It has been proposed to make the earthing coil a 'dissonance coil,' *i.e.* of such inductance that it is not in resonance with the capacity of the system, but this seems to remove the essential feature of the Petersen system whilst still leaving the possibility of resonance at harmonic frequencies.

From tests and practical experience with a 'neutral grounding reactor' (Petersen coil) in an American installation, W. W. Lewis (*Jour. Amer. I.E.E.*, Vol. 42, p. 467) concludes that the system with reactor is more like an isolated-neutral system than a grounded-neutral system from the standpoint of voltage stresses, except that excessive voltage rises due to arcing grounds are eliminated. The system with reactor has an advantage over the grounded-neutral system in that arcs are eliminated without short circuit. The reactor will probably be limited to comparatively low voltage and short systems owing to the cost of installing it on high voltage, long systems, and the difficulty of obtaining a current balance at the arc; also, its use will probably be limited to isolated-neutral systems, the operation of which is not satisfactory but on which, for some reason, it is not desired to connect the neutral straight to earth.

The value of earthing the neutral through a resistance as a protection against arcing grounds and other causes of voltage rises has been discussed by K. Edgcumbe who reaches the following conclusions:—

1. Three-phase systems with insulated neutrals are dangerous owing to their liability to transient voltage rises due to intermittent earths.
2. The connection of the neutral point of a 3-phase system direct to earth is inadvisable owing to the unlimited current which may flow in the event of an earth fault.
3. Earthing the neutral point through a resistance affords complete protection against voltage rises due to intermittent earths. It is valuable in suppressing rises due to all other causes, limits the current in the event of an earth fault, and enables advantage to be taken of leakage tripping.
4. The earthing choker is valueless on complicated systems, always involves a serious risk of resonance, offers no advantages over the earthing resistance as a means of suppressing intermittent earths, and is useless as a protection against voltage rises due to any other causes (*El. Rev.*, Vol. 90, p. 399).

352. **Failure of Insulation; Leakage Protection.**—The causes of failure in the insulation of any part of a circuit may be: (i) deterioration of the insulation by overheating (§§ 72, 80) caused by overload or otherwise; or (ii) stressing of the insulation by voltage higher than it will withstand even in its normal condition, such excessive voltage being due to any of the causes discussed in §§ 345-351. The effect of the failure is to introduce danger to life from shock; possible failure of insulation in other circuits by the admission to or near them of pressure higher than that for which they are insulated; and possible flow of leakage current which may cause damage by electrolysis, char surrounding insulation, woodwork, etc., by its heating effect and thus introduce risk of fire, or be of such magnitude as to constitute a short circuit with all its serious consequences (§ 338). To prevent failure of insulation it is necessary to avoid the causes of failure specified above.

Once insulation has failed, the only safe course is to isolate the affected portion of the circuit and repair the insulation. Theoretically a single failure in the insulation between a conductor and earth should not matter if the insulation be intact throughout the remainder of the circuit. Actually, however, the failure subjects the insulation of the other line or lines to the full voltage of the system (§§ 351, 354) and the danger of shocks is also increased. If the neutral be earthed, an earth fault on any line will result in short circuit through the resistance of the fault and of the neutral earth connection.

Theoretically, several faults may exist simultaneously without disturbing operation, so long as they are *all* on the same pole or phase, but actually there may be a pressure difference of 10 or 15 V between two points in a wiring system (much more in other cases) and this is sufficient to cause considerable leakage under favourable conditions (*cf.* rail return in traction systems, Chapter 35).

The leakage current between a nominally insulated conductor and earth may be measured by a milliammeter connected between the conductor and earth, and when the total leakage current exceeds 1 / 1 000 of the maximum current supplied steps should be taken to locate the leakage and improve the insulation of the system.

Long before the leakage from a faulty system becomes sufficient to operate overload-protection devices (§§ 342, 343) the

leakage current is dangerous, and it is desirable that the faulty section should be isolated automatically by a *leakage-protection device.* This may consist of a relay which is actuated by the leakage current itself, or it may utilise the fact that when there is leakage the algebraic sum of the currents in the three conductors of a 3-phase system is no longer zero.

In the Howard leakage detector a current transformer is connected in the earthing wire of, say, a switchboard frame, and the secondary of the current transformer is connected to a tripping relay (§ 344). Then if there is leakage to earth from the bus bars (in the example chosen) the current transformer carries the earth current and the relay trips the circuit breaker and isolates the defective bars.

In the Ferranti-Field leakage-protection system for cables, a coil connected to the trip-relay is wound on an iron core which surrounds the 3-phase cable to be protected. In the event of leakage from any one of the cable cores, the algebraic sum of the currents in the latter is no longer zero; a resultant flux therefore traverses the iron core and induces an E.M.F. in its winding which operates the relay (*see also* § 359 (i)).

Other selective or discriminative systems of protection which also isolate the defective section in the event of leakage, are described in § 359.

353. **Earthing.**—Regulation 21 of the Electricity Regulations (Factory and Workshop Acts) runs as follows:—

Where necessary to prevent danger, adequate precautions shall be taken either by earthing or by other suitable means to prevent any metal other than the conductor from becoming electrically charged.

This regulation applies at all pressures exceeding 125 V alternating or 250 V direct. The term 'earthed' as defined in the Regulations, means connected to the general mass of earth in such manner as will ensure at all times an immediate discharge of electrical energy without 'danger.' This is defined as danger to health or to life or limb from shock, burn or other injury or from fire or explosion.

Methods to be adopted and precautions to be observed in earthing specified parts of electrical systems are discussed very fully in the *Memorandum on the Electricity Regulations* * which should be consulted; for notes on Earthing in Mines see Chapter 32. It must here suffice to say that all bare metal—such as machine or switchboard frames, transformer tanks, cable sheaths

* H.M. Stationery Office, 4d. net.

(metallic), etc.—which may be rendered 'live' by leakage or by direct contact with charged conductors must be 'earthed' by connection to a suitable 'earth plate' (§ 348 and Chapter 32). In some instances the bare metal which must be earthed is used to prevent access to live parts, as in the case of metal screens enclosing switchgear; in other cases, *e.g.* motor frames, transformer tanks, etc., it is a constructional part of the apparatus. Where, as in portable apparatus, a permanent earth connection cannot be made to the frame, it is usual to provide a special earthing conductor in the cable supplying the apparatus in question, this conductor leading back to some point at which a permanent earth connection is established.

If an operator must necessarily work on or near live metal he should be provided with rubber gloves and an insulating mat or stand; and he should be prevented, by an insulating screen, from touching earthed metal. It should be remembered that it may be dangerous to touch even the insulation of conductors at high or extra-high pressure. Working on live overhead conductors is extremely dangerous and demands the utmost vigilance. It is possible to receive a fatal shock when working on a nominally dead line which runs parallel to live conductors, owing to the high-pressure charge induced by the latter (*see Science Abstracts*, Vol. 25, B, No. 1039).

354. **Earthing the Neutral.**—During normal operation the 'neutral point' of any electric circuit is at earth potential, and by connecting it to earth it is kept at this potential whatever the irregularities on the system. It is usual to make the connection between neutral and earth through a resistance which limits the current flowing in the event of a 'dead (low-resistance) earth' on one line. Iron grid resistances, water resistances, and carbon resistances are used for this purpose; carbon resistances have several advantages one of which is that the negative temperature coefficient of resistance of this material allows the current to increase gradually until the circuit breakers operate. If the neutral points of two or more paralleled machines or stations be earthed, precautions must be taken to prevent the circulation of current in the parallel earth connections.

With an earthed neutral, an earth fault on any line at once operates the circuit breakers or selective protection gear; the only disadvantage is that a shut-down may be occasioned by a

transitory break-down from line to earth. Theoretically a system with insulated neutral can be kept in service with an earth fault on one phase but there are serious practical disadvantages in such a system (§ 351).

The general import of the various British regulations on this subject is that, where the pressure of supply between the conductors of a system of mains exceeds 125 V the neutral point at the generating station, sub-station, or transformer supplying the circuit must be earthed and the insulation of the mains must be maintained efficiently at all other points; if the current passing through the connection to earth exceeds 1/1000 of the maximum supply current of the circuit, the insulation of the latter must be improved. The neutral point of the star winding of each 3-phase circuit used for extra high pressure (over 3000 V) may be connected with earth (at one point only, *viz.* the station, sub-station, or transformer) or it may be insulated. If connected to earth through a resistance the latter must be low enough to ensure that the main fuse or circuit breaker acts in the event of an earth fault. If the neutral point is not earthed a separate electrostatic voltmeter must be connected between each distinct circuit and earth, and if the indications of the voltmeters show the insulation of any of the circuits to be faulty the insulation must be restored.

355. **Low-voltage and Interruption of Supply.**—The inconvenience and financial loss (to supplier and consumer) occasioned by interruption of supply must be avoided as far as possible by securing safety and reliability in all parts of the supply system and by isolating faulty sections before the damage has time to spread (§ 357). Abnormally low voltage of supply is naturally associated with some radical defect in the supply equipment or its conditions of operation; also, supply at low voltage cannot be utilised efficiently* or, in some cases, with safety.† For both of these reasons it is necessary to interrupt the supply if the voltage becomes abnormally low (say 50 °/₀ of normal). The interruption is generally effected at the main switch of the circuit concerned so that when the voltage again becomes normal, or when supply is resumed after interruption from any other cause, full voltage may not inadvertently be applied abruptly to apparatus which was in service when the supply failed.

The 'no-volt' or 'low-voltage' release for a circuit breaker consists of a pressure-wound (*i.e.* shunt) solenoid which holds

* Even 5 % less than rated voltage involves 15-20 % reduction in the candle power of tungsten filament lamps.

† At reduced supply voltage motors require a heavier current to drive a given load; overheating then occurs. If the drop in voltage is sufficient to cause the motor to stop, the machine then short circuits the mains.

open a switch in the trip circuit as long as the supply voltage exceeds, say, 50 % of normal. Directly the voltage drops below the predetermined limit, the solenoid releases the tripping switch and the circuit breaker is opened. In the case of motors used in conjunction with starters (Chapter 29) the low-voltage device is arranged to hold the starter 'on' until the voltage becomes dangerously low, and then to allow the starter to be returned to the 'off' position by a spring so that the motor has to be re-started in the regular manner when supply is resumed.

A definite air gap is needed in the magnetic circuit of low-voltage releases to ensure that residual magnetism does not hold the device 'on' after the voltage has fallen below the prescribed limit. It is common to specify that a low-voltage device shall not hold, when switching in, if the voltage is lower than 80 % of normal and that it shall release, in service, if the voltage falls to 50 % of normal. In variable-speed motors where the field current varies within wide limits the low-voltage release may have to be connected across the mains (instead of in series with the field windings) in order that it may not open at the lower values of field current.

If the supply pressure exceeds 600 V, the low-voltage solenoid is generally supplied through a potential transformer.

Interlocks of various descriptions are used to prevent switches from being closed whilst workmen have access to parts which would then become live (§ 373).

356. **Fire Risk.**—The fire risk from the wiring, switchgear, and accessories of a domestic lighting, heating, or power installation is negligible provided that the whole of the equipment is by reputable makers and is installed in accordance with the Wiring Rules of the I.E.E. (London), or the corresponding rules of similar bodies in other countries. Similarly, the Home Office Regulations for the use of electricity in factories, workshops, mines, etc., take into consideration the special conditions of these services and compliance with these Regulations eliminates practically every risk. Fire arising from a wiring installation or its accessories can only be due to overheating, leakage, or open arcing or sparking; against all of these contingencies suitable provision is laid down by the rules and regulations mentioned. Even a 'dead short' between the conductors of a multicore cable in an explosive atmosphere is unlikely to cause fire or explosion if the circuit is

provided with proper protective devices, because the latter isolate the faulty section before the arc can penetrate the outer insulation of the cable.

The main fire risk in a modern electrical installation is probably in the oil switches and generators. In the past a number of disastrous switchboard fires have been started by oil switches being unable to interrupt safely the enormous amount of power flowing through them under short-circuit conditions. This danger has been reduced by increasing the 'breaking capacity' (§ 371) of oil switches: and the risk of any general conflagration is further reduced by the provision of vent pipes which carry oil vapour away to the open air; by the use of 'explosion proof' switch tanks; and by the use sometimes (§ 378) of a switchboard construction in which each switch is in a separate fireproof compartment, the latter having a drain for the removal of oil, should any escape. It has been proposed to fill any switch or transformer compartment, in which fire may break out, with carbon dioxide; this can be done automatically, but it is doubtful whether such equipment is necessary or, on other grounds, desirable.

In the event of arcing within the windings of a generator, due to break-down of insulation, there is a great danger of the fire being fanned and spread by the blast of air blown through the machine for ventilation (§ 146). This danger may be reduced by the provision, in the outgoing air ducts, of fusible links which release dampers cutting off the air *supply* if the temperature of the outgoing air becomes so high as to indicate fire. Probably a more reliable arrangement is to arrange that the electrical protective gear, which cuts the generator out of circuit in the event of break-down, also cuts off the air supply. At the Gennevilliers (Paris) station the generators are ventilated by air which is circulated in a closed circuit. This avoids carrying dust into the windings. A refrigerating plant is placed at one point in the air circuit, and the air is charged with nitrogen to such an extent that it will not support combustion.

To eliminate the risk of overheating and fire which would result from failure in the supply of cooling air (or water or oil) to a machine, etc., dependent upon forced cooling, automatic devices should be used to give an alarm and shut down the plant in that event.

357. Selective Protection.—In distribution networks where

large amounts of power are transmitted through interconnected cables it is imperative that a faulty machine or circuit should be isolated promptly from the remainder of the system in order that sound parts of the system may not be affected by currents flowing to the fault. The greater the degree of subdivision of the system, the smaller is the area affected by isolation of a faulty part. On the other hand, the greater the extent to which the feeders are interconnected (so as to form a network with alternative lines of supply to practically every point), the more difficult it becomes to isolate a faulty section promptly and with absolute discrimination. Overload relays with graded time elements (§ 344) offer one means of opening first the switch nearest to the fault, but if the fault can also be fed through another cable connected to the first beyond the point of break-down it is obviously necessary to isolate the fault by opening switches on both sides of it. This can be accomplished by reverse-power relays (§ 358). Alternatively, each section of the network can be protected by one or other of the special systems of selective protection described in § 359; these systems all operate on the general principle of comparing the conditions at the two ends of the portion of the circuit which they protect; in this way, it is possible to discriminate between a fault in the section protected and abnormalities due to load fluctuations or to a fault elsewhere in the network which will be cleared by other protective gear.

358. Reverse Current and Reverse-power Relays.—The simplest type of reverse-current switch is the reverse-current 'cut-out' sometimes inserted in battery-charging circuits to open the latter should the direction of current be opposite to that which is required for charging. A reverse-current switch or relay for a D.C. circuit requires only a current coil for its operation and it will act directly the current reverses. In an A.C. circuit, however, the alternating current has no definite direction of its own; the actual direction of the current reverses in each 'cycle,' and 'reversal' of an alternating current in the sense here considered can only be defined in terms of the relation between the current and voltage waves. An alternating current is said to be reversed when the relative directions of current and voltage are reversed. To determine when this is the case it is necessary to employ a device operated by both current and voltage, *i.e.* one which discriminates between forward and reverse *power*. The simplest

form of reverse-power relay for A.C. working comprises pressure (shunt) and current (series) windings which normally oppose each other; if the current 'reverses,' the two windings co-operate to close a trip circuit. Alternatively the windings may be arranged normally to assist each other; when the current is reversed an armature is released and the trip circuit is closed. The type of relay in which the pressure and current elements are normally in opposition is preferable for A.C. working.

It is obvious that either a dynamometer-type or induction-type wattmeter (§ 109) can be used as a reverse-power relay, the movement of the instrument being fitted with a contact maker in the trip circuit, instead of with a pointer. The connections are such that so long as the power is 'forward' the relay contacts are held open, but when the power reverses they are closed. The induction-type relay may operate the trip contacts through a cord wound round the spindle of the induction-disc; this provides a time element (§ 344) and prevents the main circuit from being opened by momentary reversal of power.

Reverse-power relays are used to prevent alternators or transformers from being fed by the bus bars or circuits to which they should supply power; also, to prevent a feeder-fault from being supplied through a feeder connected in parallel with the defective one. These relays cannot be used on interconnector cables which may, in normal service, have to carry power in either direction between two stations. If the main voltage becomes very low, as it may do on heavy faults, there is a risk that the reverse-power relay will not operate; and, in the past, some reverse-power relays have operated on forward power at very low power factor. Modern wattmeter-type reverse-power relays can be relied upon not to operate on forward power under any circumstances, and to operate on reverse power at pressures down to 10 % of normal voltage. For complete protection two relays are needed in a 3-phase system with insulated neutral, and three relays if the neutral be earthed.

359. **Selective Protection Systems.**—The principal systems of selective protection for feeders, generators, and transformers are described below and their general characteristics are indicated. The automatic protection of electrical networks and apparatus is a specialised branch of engineering with an extensive literature of its own, but it is desirable that every electrical engineer should be familiar with the main principles of the subject.

The 'pilot' wires used in some protective systems have only to carry weak, low-voltage current for the operation of relays; they are therefore of small cross-section and have relatively light insulation. The pilot circuit in the Merz-Price balanced voltage system of protection as applied to a 3-phase feeder, generally consists of a three-core 7/·029 low pressure cable; provided that the pilot cable is connected to current transformers at each end of the feeder, as in Fig. 62, it need not be laid along the same route as the feeder. 'Sheathed' pilot cables are virtually three-core concentric cables, each pilot wire being provided, outside its main insulation, with a thin metallic sheath for reasons explained at (*c*) below; the sheaths are insulated from each other by a light external covering.

The construction of split-conductor cables, in which each of the halves of the main conductor acts as pilot wire to the other half,

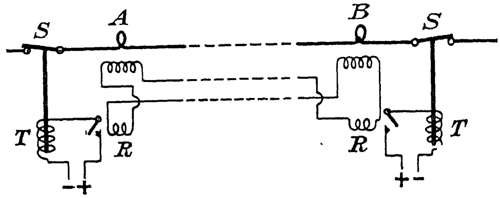


FIG. 62.—Merz-Price balanced voltage system for feeder protection. (Connections for one phase only.)

is illustrated in Figs. 66, 67 (Sec. (*d*) below). The insulation required between the two 'splits' of each phase is only that needed to withstand the P.D. existing between the splits under fault conditions. Normally, the halves of a split-conductor carry equal currents and there is no P.D. between them and any cross-section of the cable.

(*a*) *Merz-Price Balanced Voltage System.*—This system is used for the protection of feeders and depends upon the balancing of E.M.F.'s induced in current transformers placed at each end of the feeder and connected by 'pilot' wires. Fig. 62 shows the connections for one phase only, for simplicity. The secondaries of the current transformers *AB* are connected in opposition so that, normally, no current flows through the relays, *RR*. On the occurrence of any fault in the feeder, the main current at *B* no longer equals that at *A*, hence current flows in the relay circuit and the switches *SS* are tripped by *TT*, completely isolating the defective feeder. The direction of the main current is immaterial hence the system is applicable to ring mains. It is essential that the transformers *AB* should balance at all loads as long as the feeder is sound and, in order that the current-voltage characteristic may be linear the transformers have air gaps in

their magnetic circuits. Owing to the electrostatic capacity of the pilot wires and the high P.D. between them when the feeder current is heavy, there is then a considerable capacity (condenser) current flowing through the pilot wires. This may operate the relays unnecessarily unless their setting is relatively insensitive. The difficulty is overcome by the use of sheathed pilot wires (*see* (*c*) below).

(*b*) *Merz-Price Circulating Current System.*—This system, which is used for the protection of alternators and transformers, is shown in Fig. 63 as applied to a 3-phase alternator *G*. Current transformers are placed at *A* between the alternator phases and the neutral point *N*, and at *B* between the alternator and the main switch *S*. The current transformer secondaries are connected in series with compensating resistances *r*. During normal operation a current of about 5 *A* circulates through the secondaries of the current transformers and the pilot wires, but there is no current through the relay coils connected between the pilot wires and the neutral. On the occurrence of a fault the current balance in the pilot wires is disturbed, the relays *R* are operated, and the trip coil *T* opens the main switch *S*.

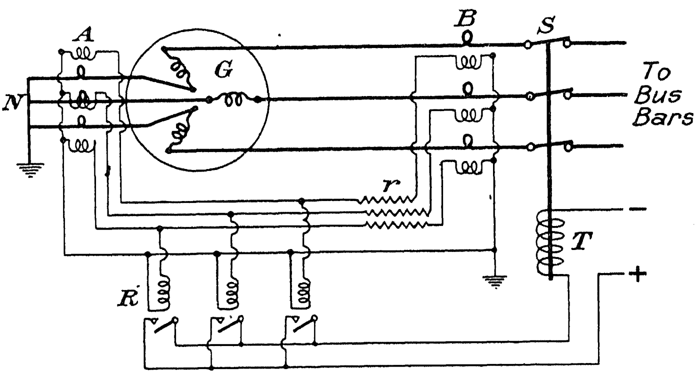


FIG. 63.—Merz-Price balanced current system for generator protection.

Ordinary instrument transformers are used, without air gap in the magnetic circuit. If the system be applied to the protection of, say, a 6 600 / 440 V, delta / star transformer, with a 10 : 1 star-connected instrument transformer on the high-voltage side, the low-voltage instrument transformer would be delta-connected, and its ratio would be $(10 / 1) \times (6\,600 / 440) \times \sqrt{3} = 260 : 1$.

This system of protection is more sensitive and stable than the balanced-voltage system, but it is inapplicable to feeders because the resistance of the pilot wires would then be prohibitively high. The current in the pilot wires is proportional to the main current, hence fuses in the former provide overload protection.

(*c*) *Beard-Hunter Sheathed-pilot System.*—This system is identical with the Merz-Price balanced voltage system (Fig. 62) except that the capacity current trouble mentioned at (*a*) above is eliminated by providing each pilot wire with a sheath *l*, *m* (Fig. 64). The sheaths are interrupted at the centre as shown, and from a study of the connections in Fig. 64 it will be seen that the capacity currents no longer pass through the relay windings, hence the relays may be set more sensitively than in the Merz-Price system.

(*d*) *Merz-Hunter Split-conductor System.*—Referring to Fig. 65, there are used, in each phase of the line, two conductors of equal electrical resistance connected in parallel at each end of the length to be protected, but otherwise insulated from each other. Under normal conditions, the total current in each phase is divided equally between the pair of conductors, but when a fault occurs this balance is disturbed.

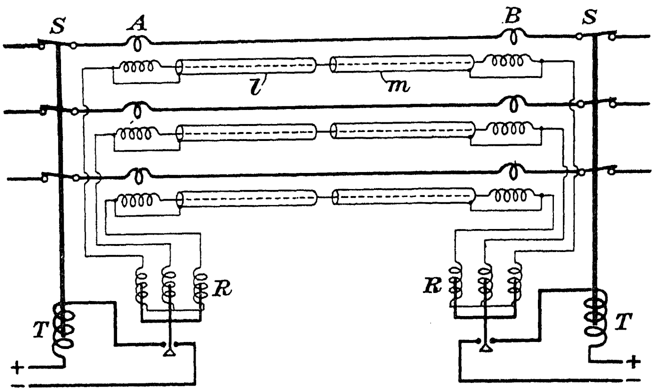


FIG. 64.—Beard-Hunter sheathed-pilot system for feeder protection.

The two conductors of each phase are wound in opposite directions on current transformers at *A*, and so also at *B*. Under normal conditions, no current flows through the trip relays *R*, but directly the current balance in the 'split conductors' is disturbed, the relays *R* operate at both ends of the section and the trip coils *T* open the switches *S*. No pilot wires are required, but the main cables must be

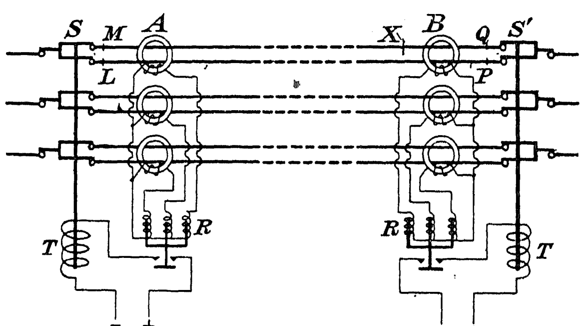


FIG. 65.—Merz-Hunter split-conductor system for feeder protection.

specially constructed on the split-conductor principle. A cable with six electrically identical cores (Fig. 66) may be used with two cores in parallel for each phase, or each phase may be served by two concentric cores (Fig. 67) * in which case the inner and outer must be transposed at intervals to maintain equal impedance in both halves of the split conductor.

* The overall diameter may be reduced by using concentric elliptical cores.

This protective system can be set for very low fault currents without risking disconnection of sound feeders. It will be seen that the 'split' is continued through the switches S at each end; this is to ensure that when one set of switches S' is opened, the other set also opens. If the splits were joined at LM and PQ, a fault at X (near the end of the cable) would cause the switch S' to open, but the impedance of the paths $LPQX$ and MX would be so nearly equal that the switch

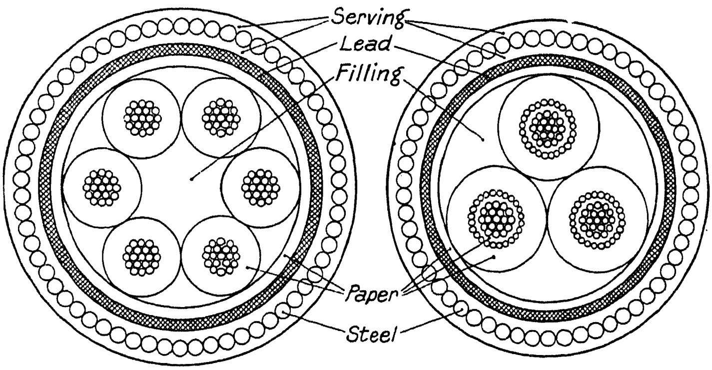


FIG. 66.—Six-core cable for 3-phase split-conductor system.

FIG. 67.—Three-core concentric split-conductor cable.

S would probably remain closed. With the split continued through the switches, current can only flow along MX after S' has opened, hence A is unbalanced and S also opens.

The split-conductor system is hardly suitable for pressures exceeding 20 000 V because the size of the individual cores is small (for the amount of power which it is desirable to transmit by a single feeder) and the stress on the insulation is therefore severe (§ 288).

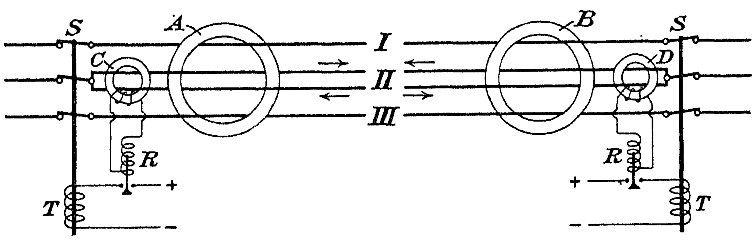


FIG. 68.—Hunter 4-core pilotless system for feeder protection.

(e) *Hunter Four-core Pilotless System.*—This system is a combination of the Merz-Price balanced voltage and the split-conductor systems. One phase (II in Fig. 68) is protected on the split-conductor system whilst the other phases are protected on the Merz-Price system, using the splits of phase II instead of pilot wires. Any fault on phase II causes the transformers C, D to be excited and the switches S to be tripped. On the balancing transformers A, B the phases I and

III are in opposition to the splits of phase II, and are also in opposition to each other. Normally, A and B produce equal and opposite E.M.F.'s in the splits as shown by the arrows, but in the event of any fault on I or III, this balance is disturbed, a circulating current flows round the splits of phase II, and the transformers C, D cause the switches S to be tripped.

(*f*) *Beard Self-balance System.*—The application of this system to alternator protection is shown in Fig. 69. The line and neutral connections of each phase winding are taken through a transformer which is connected to the tripping relay. In the event of a fault to earth or between phases the incoming and outgoing currents are no longer equal, the transformer T is excited, and the relay is operated. If the neutral leads be carried to the switchboard (the neutral connection and the transformers T being then at the switchboard), this system protects against faults in the cables between generator and switchboard, as well as in the generator itself.

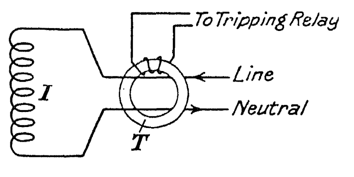


FIG. 69.—Beard self-balance system. (Connections for one phase only.)

(*g*) *McColl Biassed-Relay System.*—Referring to Fig. 70, current transformers CT are installed at each end of the feeder, and each transformer is connected to two circuits in parallel, one of these being dotted in Fig. 70 for the sake of clearness. The pilot wires form one branch from the secondary of each transformer, and the other branch (dotted in the figure) is formed by the operating coil O of a differential relay and a resistance r, which is adjusted so that this circuit is of the same resistance as one of the pilot wires. The restraining coils R of the relays are connected one in series with each pilot wire. The fulcrums of the beams carrying the relay plungers are nearer the operating coils than the restraining coils, hence the latter exert the greater moment (with equal currents in O and R) and the relay has a bias to hold open the trip contracts T.

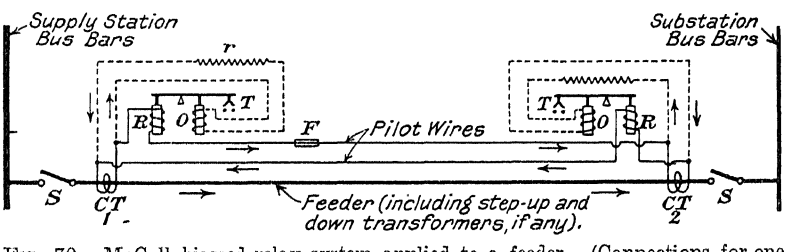


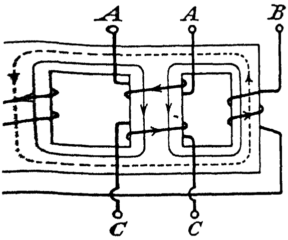
FIG. 70.—McColl biassed-relay system applied to a feeder. (Connections for one phase only.)

So long as the feeder is sound, the current transformers at each end deliver equal currents, and the currents in the operating and restraining coils of each relay are equal, hence the beam is held down by R and the trip contacts remain open. If a fault occurs in the feeder, the secondary current delivered by the transformer $CT - 1$ is greater than that delivered by $CT - 2$, the difference between these currents dividing between the duplicate circuit (dotted) at the left-hand station, and the duplicate circuit at the right-hand station. Since the latter circuit is, with regard to $CT - 1$, in series with both pilot wires, the total resist-

of this path is three times that of the duplicate circuit at the left-hand n. As a consequence, 75 °/$_0$ of the excess current flows through the operating f the relay in the supply station, and the trip contacts T are closed if the onal pull now obtained at O is sufficient to overcome the initial bias of the The action of the relay depends entirely upon the relative magnitude of irrents in its two windings regardless of the actual value of the main current. tly the trip contacts T are closed, the oil switch S is opened in the usual the trip circuits themselves are not shown in Fig. 70.

During normal operation, current circulates continuously through the pilot . If the latter be broken accidentally, the whole output of each current former is diverted through the operating coil of its relay and the trip circuit sed. If a fuse F be inserted in the pilot circuit, this melts in event of sus- a overload, and by opening the pilot circuit causes the relays to operate. equipment then gives protection against overload as well as against faults in eeder.

h) *British Thomson-Houston Biassed Transformer System.*—In this system s made of a special transformer, which is illustrated diagrammatically in Fig. The 'operating' coil AA produces a flux as shown by the solid lines and this



71. — Illustrating the inciple of the biassed insformer.

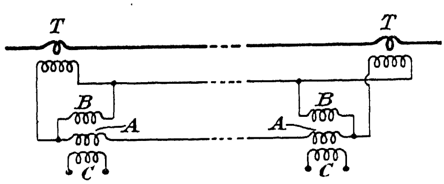


FIG. 72.—B.T.H. biassed transformer system applied to a single-phase feeder.

ces an E.M.F. in the secondary winding CC which is connected to the trip y (not shown). The 'restraining' or 'biassing' winding BB produces a flux own by the dotted line; this has no direct effect upon the winding CC, but ncreasing the flux density in the iron which it traverses, the biassing flux ts the ratio of transformation between the windings A and C.

Fig. 72 represents the application of the system to the protection of a single- e feeder. The general principle of the protection is the same as in the Merz- balanced voltage system (Fig. 62) except that the trip relay is served by the sformer AC instead of being connected directly in the pilot circuit. The nctive feature of the system here described is the addition of the biassing coils which are connected across the secondary terminals of the current trans- ers TT, and therefore carry a current the magnitude of which varies with the n current. As already explained, the ratio of the transformer AC depends n the value of the current in the biassing coil B, hence the sensitivity of the bination is greater, the lower the load on the feeder. The amount of restraint egligible up to full load on the feeder but, under overload conditions, the sing transformer prevents the relay from being operated by: (i) Capacity ents in the pilot wires of a sound feeder; or (ii) currents in the pilot wires to imperfect balancing of the transformers TT.

In a 3-phase system this method of protection can be used in conjunction

with separate 'earth relays' and 'line-fault relays;' and the former can be set for maximum sensitivity because they are not affected by the heavy currents which flow through the line-fault relays when a sound feeder is carrying short-circuit currents to a fault beyond. For further information *see El. Rev.*, Vol. 90, p. 928.

(*i*) *Ferranti-Hawkins Core-balanced System.*—This may be described as a combination of the Merz-Price and the Ferranti-Field (§ 352) systems. Selective protection is obtained, but against earth faults only (which, in practice, always

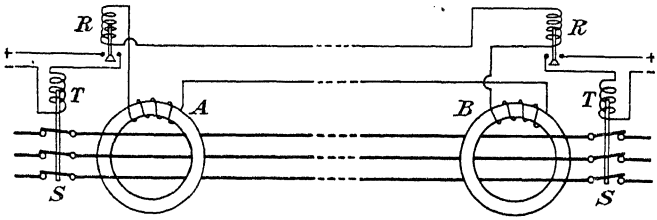


FIG. 73.—Ferranti-Hawkins core-balance system of protection against earth faults.

accompany faults between phases on feeders). A ring-type transformer surrounds the 3-phase cable at each end (*AB*, Fig. 73) and, as long as the cable is sound, the currents in the 3-phases (whether balanced or not) produce no field in the transformer cores. Directly an earth fault occurs, the vector sum of the currents in the cable is no longer zero, the relays *R* are excited and the main switches are tripped.

(*j*) *Bowden-Thompson Sheathed Cable System.*—The main cables used in this system are provided with thin metallic sheaths between and insulated from the cores, and between the cores and the lead sheath. Thus, in Fig. 74, *L* represents the sheath between cores, and *M* that between the cores and the lead sheathing. Any fault between the cores necessarily reaches the sheath *L* before the main cores are affected; the current which then flows through the transformer *B* to earth excites the relay *R* and causes *T* to trip the main switch *S*. An incipient earth fault reaches the sheath *M* and trips the main switch in the same way before the fault reaches the lead sheath. If the cable be damaged from outside, the sheath *M* is earthed before the main core and, since *M* is maintained at a potential different from that of earth (by the transformer *C*), a current now flows through *B* and the switch is tripped as before.

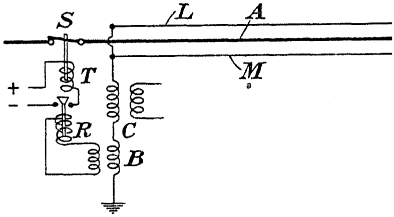


FIG. 74.—Bowden-Thompson sheathed cable system.

Other systems have been devised for the automatic selective protection of A.C. circuits and apparatus, and there are many modifications of the systems described above, but the notes here given cover the main principles of the art. The relative merits of the various systems of protection is a subject beyond the scope

of them with some of the factors involved are: The capital cost of the protective equipment (including pilot wires and special cables, if any); the possible sensitivity of setting, consistent with stability; the type of transformers required in the protective system and the extent to which the characteristics of transformers must be balanced to prevent unwarranted shut-down; and the extent to which the protective gear is unaffected by normal fluctuations of load and by faults in zones for the protection of which it is not responsible.

360 Bibliography (see explanatory notes, § 58).

Regulations.

Acts, § 356, and various regulations by the Electricity Commissioners.

B.E.S.A. Standards.

Specification for Low-pressure Electric Cut-outs.

Books.

Theory and Calculation of Transient Electric Phenomena and Oscillations. C. P. Steinmetz (McGraw, Hill).

Protective Systems and Gear. J. Henderson and C. W. Marshall (Benn). See also § 356.

I.E.E. Journal.

Merz-Price Protective Gear and other Discriminative Apparatus for Alternating-current Circuits, K. Faye-Hansen and G. Harlow. Vol. 46, p. 671.

Earthed versus Unearthed Neutrals on Alternating Current Systems, J. S. Peck. Vol. 50, p. 150.

Pressure Rises, W. Duddell. Vol. 52, p. 1.

Current-limiting Reactances on Large Power Systems, K. M. Faye-Hansen and J. S. Peck. Vol. 53, p. 511.

Automatic Protective Switchgear for Alternating-current Systems, E. B. Wedmore. Vol. 53, p. 157.

Control of Large Amounts of Power, E. B. Wedmore. Vol. 56, p. 269.

Some Transient Phenomena in Electrical Supply Systems, E. W. Marchant, Vol. 56, p. 445.

Protection of Alternating Current Systems without the Use of Special Conductors, Major K. Edgcumbe. Vol. 58, p. 391.

Automatic Protective Devices for Alternating-current Systems, A. E. McColl. Vol. 58, p. 525.

Earthing: Report of the Earthing Sub-Committee of the Wiring Rules Committee. Vol. 58, p. 468.

Protection of Alternating-current Circuits and Apparatus, E. T. Norris. Vol. 58, p. 750.

Aluminium Electrolytic Arrester with an Introduction on Electrical Disturbances, A. G. Ramsey. Vol. 57, Supp., Part 2, p. 306.

Protective Apparatus for Turbo-Generators, J. A. Kuyser. Vol. 60, p. 761.

Mechanical and Electrical Effects of Large Currents on High-tension Switchgear, C. C. Garrard. Vol. 60, p. 887.

Miscellaneous.

Some Protective Relays for A.C. Circuits, Kenelm Edgcumbe. *El. Rev.*, Vol. 69, pp. 136, 163, 231.

Protective Devices against Earth. *Electron*, May 25, 1923, p. 565.

SWITCHGEAR AND SWITCHBOARDS.

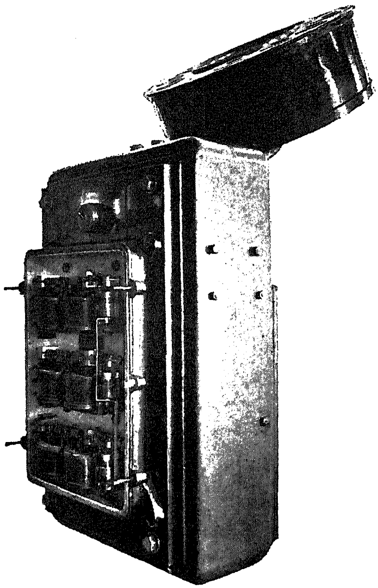
361. Functions of Switchgear and Switchboards.—The general purpose of 'switchgear' is to make and break circuits, thus controlling the operation of electrical apparatus; and the term 'switchboard' is generally applied to the group of switches, measuring instruments, and indicating devices which are used for the control of a particular circuit or an extensive network as the case may be. When the circuit is 'made,' the switchgear must be capable of carrying safely the current which flows, but as regards breaking the circuit, it is necessary to discriminate between: (*a*) 'isolating switches' (§ 362) which are suitable only for isolating a circuit *after* the current flow has been interrupted by other means; (*b*) non-automatic 'switches' (§§ 363-367, 374), which are suitable for breaking a load current; and (*c*) automatic 'circuit breakers' (§§ 365, 367), which are capable of interrupting abnormally heavy currents such as those flowing to a short circuit (§§ 339, 370). (*Note.*—Switching in lighting and other domestic installations is discussed in Chapters 21, 22; and motor control is dealt with in Chapter 29.)

362. Isolating Switches.—These switches, which are not suitable for breaking a load current, are used to isolate high-tension apparatus from the rest of the circuit and to sectionalise high-tension circuits. For example, an isolating switch is generally provided between an oil switch and the bus bars, and on the other side of the oil switch as well if the latter controls ring mains.* By opening the isolating switch (or switches) the oil switch can be made completely 'dead' and therefore safe for access to all its parts. The isolating switch consists of one or several copper blades which engage with spring contact clips

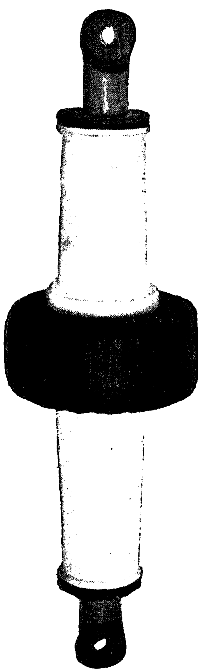
* Sometimes an isolating switch is provided between the generator and the main oil-circuit breaker but this is unusual, for it is generally expected that the circuit breaker can be attended to when the generator is shut down.

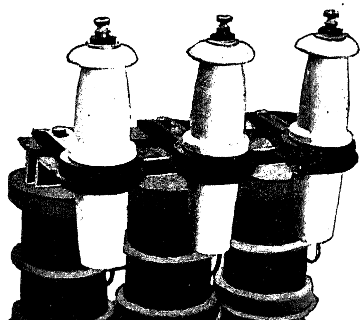
McColl Biassed Relays.

The relays shown form part of the protective gear in a large British power house and are connected to a 15-mile, 33 000 V feeder. The biassed relay operates when the fault bears a definite relation to the load on the circuit.



General Electric Co., Ltd. (London).



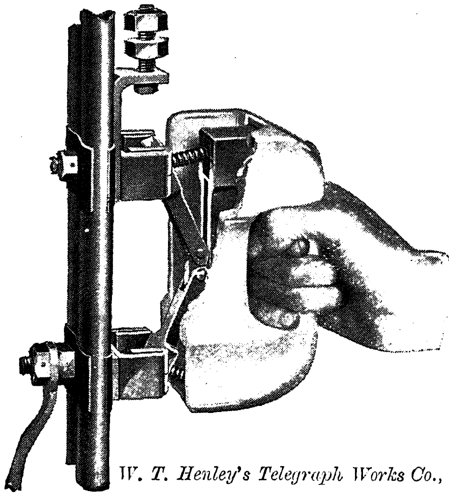


Everett, Edgcumbe & Co., Ltd.

Current and Potential Transformers.

The current transformer (left) is suitable for use on a 12 000 V system. The straight-through primary prevents breakdown due to surges; and the ring-type core, without joints, secures constant ratio and absence of phase displacement between primary and secondary currents. The three-phase potential transformer (right) is for a 6 600 V system. The primary is sectionalised to reduce the voltage between layers, and the whole transformer is impregnated with insulating compound to exclude dust and moisture. For higher pressures potential transformers are generally oil-insulated.

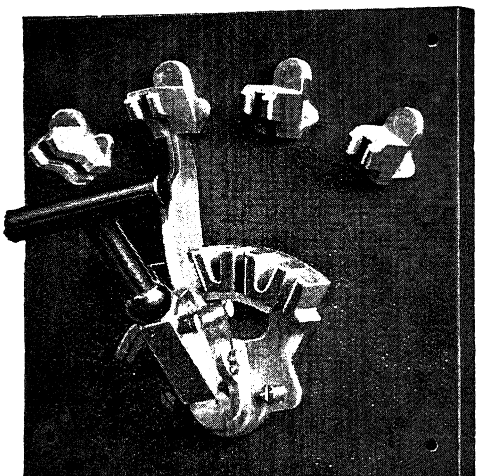
[*To face p.* 514.



W. T. Henley's Telegraph Works Co., Ltd.

PORCELAIN HANDLE WITH QUICK-BREAK ISOLATING LINKS.

This equipment is interchangeable with a porcelain-grip fuse carrier, and can be used to disconnect a circuit whilst carrying load. It serves the dual function of isolating link and knife switch, and can be used in distribution pillars or other applications where there is not room for an ordinary knife switch. The main copper link has an auxiliary 'flicker blade' for each contact, and the tension on the springs of the flicker blades is limited by a stop.



Dorman & Smith, Ltd.

SINGLE-POLE MULTIWAY SWITCH WITH QUICK-BREAK ACTION.

This switch is made for currents from 50 to 300 A, 250 V, and with 2, 3, 4, or 5 'ways.' Contact jaws are provided for both ends of the multiple copper blades so that the swivelling hinge portion is not relied upon to carry current. When the T-handle is drawn fully 'off' the switch can be turned to left or right for closing on the desired 'way,' without touching other jaws in passing. A spring poppet registers the blade into alignment.

[To face p. 515.

mounted on insulators. The circuit leads are connected to the two contact clips and the isolating blade or link is withdrawn when the circuit is to be opened. The switch blade may be pivoted in one of the contact pieces or at an independent fulcrum, and it is operated either by an insulated handle on the blade or by an insulated pole with a hook which engages in a ring on the switch blade. The conductors to and from an isolating switch should be as nearly as possible in line with the switch blade in order to reduce the mechanical force which tends to open the switch under short-circuit conditions (§ 338). If the power operative on short circuit exceeds 15 000-20 000 kVA the isolating switch blade should be held by a latch or bolt which must be released before the switch can be opened. Wherever possible an air-break isolating switch should be interlocked with an oil switch so that the former can only be opened or closed when the oil switch is in the 'off' position.

Isolating switches of modified design can be used, when neither making nor breaking a load current, as 'selector' switches to prepare for the closing of the circuit (by a switch or circuit breaker) on any one of two or more alternative paths. An oil-immersed isolating switch can be used to interrupt a moderate flow of power, as when sectionalising bus bars, when the duty of the switch is rather to transfer load from one part of the system to the other than to interrupt the flow completely; for the latter purpose a load-current switch or circuit breaker must be used.

363. Knife Switches.—The B.E.S.A. Report, No. 109, defines a knife switch as one in which the moving element takes the form of a current-carrying hinged blade, moving in its own plane, and entering or embracing the circuit contacts. So far as high-tension circuits are concerned such a switch is simply an isolating switch and is not suitable for opening a circuit when carrying load current. For low-tension circuits the knife switch may be used to interrupt a load current, but in order to reduce the damage caused by arcing at the contacts when the blade is withdrawn, it is usual to provide a 'quick-break' device. This generally consists of an auxiliary blade pivoted on the inner edge of the main blade; when the latter is withdrawn the auxiliary blade is held for a time by the contact clips, and the pull on a spring between the main and auxiliary blades increases as the main blade is moved away. At a certain stage in the movement, the pull on the auxiliary blade

becomes so great that this blade leaves the contacts; it is at this moment that the circuit is broken, and as the auxiliary blade leaves the contacts at high speed (whatever the speed of the main blade), there is very little destructive arcing.

The inner contact may be at the hinge of the blade, but by using a separate pivot block (in line with two contacts which are used only as contacts) it becomes unnecessary to pass current through the hinge, and the further advantage of a double-break (§ 368) is obtained. For very heavy currents (up to 15 000 A) a number of switch blades are mounted on a common spindle and fitted with a common handle; the blades are interleaved with up-standing plates at the hinge, and when the switch is closed the blades penetrate between similar plates forming the fixed contact; in switches of this type for 3 000 A or heavier current, clamping bolts are used to hold the blades in close contact with the contact plates. In the blade itself the current density may be 800-1 000 A per sq. in., but at the contacts it should not exceed 80-100 A per sq. in. of contact surface with spring clips. If the contact surfaces be clamped by a bolt, the current density is usually the same as for rubbing contacts save for the slight increase occasioned by the slot which is necessary in order that the bolt may be inserted into the contact.

Multipole knife switches consist of two or three blades insulated from each other, but coupled mechanically by a bridge piece, or mounted on a square shaft, so that they can simultaneously be moved into or out of the circuit contacts of a 2- or 3-wire circuit. This is generally the most convenient way of ensuring that a circuit is completely isolated from the supply; opening a switch in one wire of a 2-wire circuit, two wires of a 3-wire circuit, interrupts the flow of current, but the circuit remains 'live' through the switch in the other line.

The contact blocks of knife switches may be provided with lugs for the 'front connection' of the circuit wires or they may have stems which go through the base or panel on which the switch is mounted so that the leads may be attached by 'back connection.' The latter arrangement is safer and is generally employed. In knife switches with multi-blade contacts it is usual for the plates to pass through the panel and form the rear connection as well as the contact connection. This avoids joints in the fixed contacts and enables good contact to be obtained between

the strap conductors at the rear and the terminal of the knife switch. The use of screwed studs and nuts is to be deprecated for very heavy currents and the strap type of contact is generally used for circuits of 1000 A and upwards.

A 'throw-over' knife switch is provided with two sets of circuit contacts on opposite sides of the blade hinge. If the hinge block forms one of the circuit terminals, the switch can only be used as a two-way switch, for the purpose of connecting the circuit at the hinges to either of the two circuits which terminate at the other contacts. If, however, each blade has an independent pair of circuit contacts on each side of the hinge (the latter not carrying current), the switch can be used to complete either one of two circuits which may be electrically independent. The 'throw-over' knife switch is often useful in that it allows either, but not both, of two connections to be effected and thus, for example, prevents alternative sources of supply from being connected simultaneously to a circuit. In its 'off' position a throw-over knife switch stands perpendicular to the base on which the contact blocks are mounted.

The common 'tumbler' switch (Chapter 21) as used in house-lighting branch circuits is a quick-break knife switch, but for mechanical reasons the details of construction differ from those of the knife switches used for heavier currents. A spring-actuated quick-make mechanism is sometimes embodied in tumbler and knife switches (in addition to the quick break), to eliminate the sparking and overheating which would occur if the switch were closed very slowly.

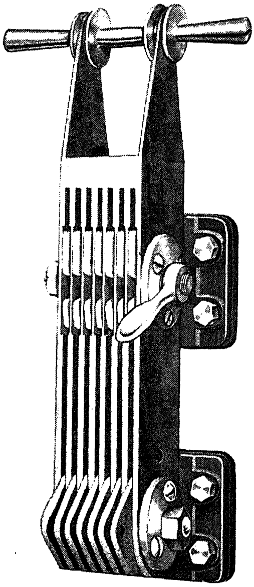
364. Horn-Break Air Switches.—An ordinary air-break knife switch is not suitable for use in high-voltage circuits, and is generally limited to pressures not exceeding 660 V; but if such a switch be used in conjunction with a horn gap it is applicable to switching on high-tension overhead lines. One terminal of the horn gap carries one of the circuit contacts of the knife switch, and the blade of the latter is carried by an insulator attached to the operating mechanism. The switch blade carries the other horn and it is arranged that the main contacts open before the circuit is broken; the break occurs on the arcing connections, some distance away from the main contacts, and the arc is then extinguished automatically (§ 346). The switch is operated from ground level by means of any convenient linkwork. Prior to the introduction of oil switches, horn-break air switches were

used on high-tension circuits in stations, but they are now used only for outdoor service.

365. **Air-Break Circuit-Breakers.**—Every switch breaks a circuit when it is opened, but the term 'circuit-breaker' is reserved for mechanical devices which break (automatically unless otherwise specified) a circuit under abnormal conditions. These conditions may be low voltage, reverse power, overload or a combination of these, but a circuit breaker must be capable of interrupting excessive current without injury, whatever the other conditions of the circuit. It is therefore necessary to make arrangements for reducing arcing to a minimum, both in degree and duration, and for preventing the main contacts from being damaged by such arcing as does occur.

In this type of switch the circuit contacts are generally heavy blocks of copper mounted on a slate or marble base from which they are insulated by mica. The contact-making element is a laminated bridge piece built up from springy strips of phosphor-bronze or copper with a steel backing strip outside. The ends of this arched bridge piece are cut at such an angle that, when the switch is closed, the strips make end-on contact with the fixed contact blocks. The angle between the plane of the strips and the face of the contact blocks is about 45°,* so that as the laminated 'brush' is pressed on to the contacts, usually under considerable mechanical pressure exerted by a toggle mechanism, there is a wiping and bedding action at the ends of the strips. The main contacts are thus 'self-cleaning' and the resilience of the laminated brush makes it possible to obtain good contact over a large area, as is necessary for heavy currents. In order that there may be no deterioration of the main contact surfaces by arcing, the moving system carries auxiliary copper contacts (electrically in parallel with the main contact brush) which make contact before, and break contact after, the main brush. The moving system also carries light fingers which terminate in renewable carbon blocks; the latter make contact with similar carbon blocks on the fixed contacts *before*, and break contact *after*, the auxiliary copper fingers. Thus, referring to Fig. 75 (*a*), when the circuit breaker opens, the

* This result is sometimes obtained by using a brush built up of flat strips, cut away at about 45° at each end, and bedding on contacts with inclined faces (*cf.* the faces of a mitred joint in a picture frame).



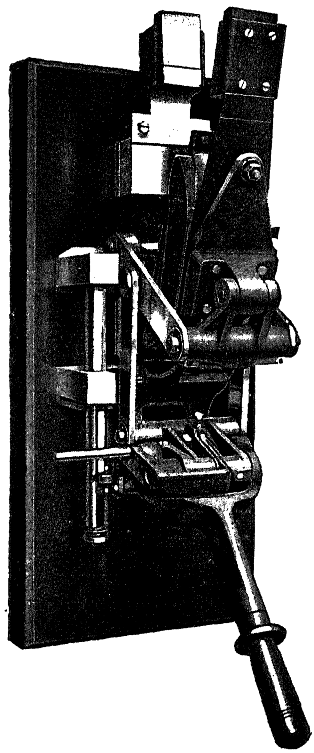
Ferguson, Pailin, Ltd.

MULTIBLADE KNIFE SWITCH FOR HEAVY CURRENTS.

This type of switch has been standardised in sizes from 300 A to 10 000 A carrying capacity. The strips forming the contact jaws pass straight through the panel and form the terminals for connections at the back. This decreases the number of joints and reduces the voltage drop; also, the fixing bolts are independent of parts carrying current. The hinge and contact jaws on the sizes from 4 000 A upwards are provided with clamping bolts, and with a permanent handle which eliminates the use of spanners.

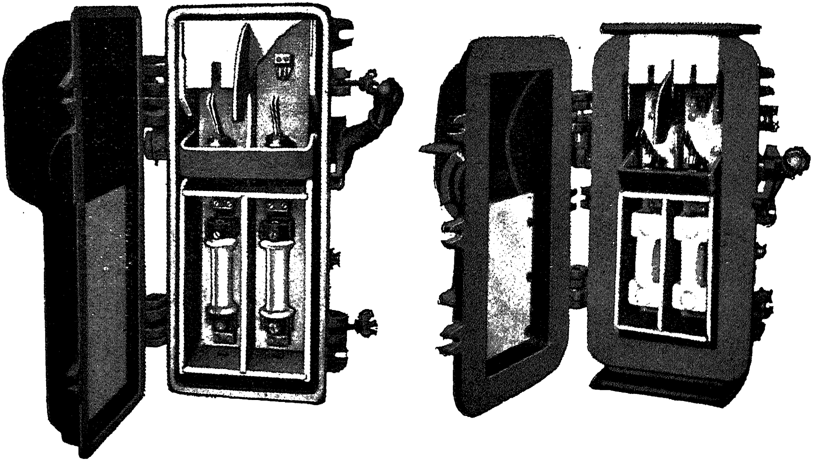
AIR-BREAK D.C. CIRCUIT BREAKER.

The breaker illustrated is rated at 2 000 A and is suitable for use on D.C. circuits up to 660 V. The laminated main contact brushes are protected by two sets of copper-to-copper auxiliary contacts and by carbon arcing-contacts. The mechanism is of the 'free-handle' type, and a quick break is obtained without the use of auxiliary springs, the breaker tripping free of the mechanism. The closing mechanism is of the toggle type, and the tripping plunger (gravity controlled) rises freely before striking the trip lever.



British Thomson-Houston Co., Ltd.

[*To face p.* 518.



General Electric Co., Ltd. (London).

INDUSTRIAL AND FLAMEPROOF IRONCLAD SWITCHES.

These photographs afford an interesting comparison between an ironclad switch (on the left) designed for general factory service and one (on the right) designed for use in mines or other places where the atmosphere may be explosive. In both instances the switch is interlocked with the case so that the latter cannot be opened while the switch is closed, neither can the switch be closed while the case is open. An insulating fireproof arc shield and barrier over the contacts eliminates the risk of short-circuiting on overload. The case of the flameproof switch is particularly robust, and the wide machined flanges of the joint cool the gases expelled in the event of an internal explosion, thus preventing the ignition of an explosive atmosphere outside.

[*To face p.* 519.

main contacts, A, open first, without sparking since the current is simply transferred to the auxiliary copper fingers; the auxiliary copper contacts, B, carry the load only for a small fraction of a second, and before they have time to become dangerously overheated, they leave the fixed contacts, thus transferring the load to the carbon arcing tips, C. The actual breaking of the circuit occurs as the moving carbon contacts leave the stationary ones. By this time the whole moving system of the circuit breaker has acquired considerable speed, hence there is a 'quick-break' between the carbon tips. Also, carbon is a 'non-arcing' material (§ 66) and is much less damaged than copper tips would be; when necessary, the carbon tips can be easily and cheaply renewed. The carbon tips are at the top of the switch so that the rising arc can damage no other part.

Circuit breakers of the above type can be built to carry 10 000 A or even heavier currents, and are used extensively in D.C. and A.C. systems, usually for pressures not exceeding 660 V. Circuit breakers for moderate currents (up to 250 A or so) may have simply the main contacts and carbon arcing tips, and the moving contact may be in the form of a wedge-shaped bar which engages between springy, tapered circuit contacts.

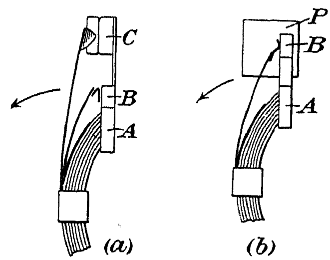


Fig. 75.—Main and auxiliary contacts in air-break switches with laminated brushes (diagrammatic).

In some cases a *magnetic blow-out* is added to assist in extinguishing the arc. This consists of a powerful electromagnet,* P, Fig. 75 (b), which establishes a magnetic field at right angles to the length of the arc between the fixed and moving contacts at B. In this case the switch has only the main laminated contact at A and the renewable copper sparking tip at B; it is not usual to employ carbon arcing tips as well as a magnetic blow-out. The

* Connected between the circuit contact and the line so that it carries the current which is to be broken. If the current is alternating, the blow-out field reverses with the current and the blow-out action is unidirectional. Though theoretically applicable to A.C. switches, the magnetic blow-out is generally used on D.C. switches only. The reactance drop in the magnet coil (which must be in series with the main circuit) is objectionable where A.C. is concerned.

sense of the field is such that the arc, which is a current-carrying conductor, is driven upwards (§ 35) on arcing horns (§ 364) and, being thus lengthened, it is quickly extinguished. If there is any difficulty in providing a large clear air space for the dissipation of the arc, the surroundings (particularly any metal with which the arc might come in contact) must be protected by fireproof, insulating shields.

366. Ironclad and Flame-proof Air-break Switches.—The distinction between ironclad and flame-proof switchgear is mainly one of degree. A 'flame-proof' switch is enclosed by a case which will withstand without injury the explosion within it of a maximum-explosive mixture of methane and air (or an equivalent explosive mixture); also, it will not transmit ignition from the internal explosion to a surrounding atmosphere of explosive composition under any conditions of service within its rating. These two requirements are fulfilled by making the containing case of great mechanical strength and by providing it and its cover with wide machined joints which permit the escape of gases produced by an internal explosion, but cool them well below the ignition point of the outer explosive atmosphere before the latter is reached. The term 'ironclad,' on the other hand, is generally applied to switches which are not flame-proof, but which are enclosed by an iron casing sufficient to protect the switch against mechanical damage, tampering or accidental contact, and drippings of water, etc.* These distinctions are of a mechanical nature, and the same electrical considerations apply whether the switch be enclosed by light sheet metal or by a flame-proof, mining-type casing. The metal casing and the operating handle (if of metal) must be efficiently earthed. There must be adequate clearance and insulation resistance between all live parts of the switch and the metal enclosure; an insulating barrier, acting as an earth shield, should be provided between the poles; and an insulating lining should be fitted to prevent any arc which may arise in service from reaching the casing. The switch itself, which should be capable of interrupting safely at least 50 % higher than its rated current

* Hitherto the term 'ironclad' has been used loosely to describe switches which differed greatly in the degree of their protection against mechanical injury, weather, etc. It is obviously preferable to distinguish between mere mechanical protection (by expanded metal, etc.), total enclosure, drip-proof, and weather-proof protection, as in the case of electric motors.

differs only from the corresponding open type air-break switch in mechanical details to suit its enclosure. An interlock (§ 373) is necessary between switch and cover so that the security afforded by the latter cannot be lost by the switch being used with the cover open.

Ironclad switchgear is commonly provided with a hemp or asbestos packing in the cover joint, but if any such packing be used in the joints of flame-proof switchgear a flame-proof vent must be provided in the casing for the relief of internal pressure. Cables are taken into the casing through suitable weather-proof or flame-proof fittings, as the case may be, and the connections to the switch are on the face of the slate or marble panel which carries the switch.

Ironclad and flame-proof switches (single, double, or triple pole) are generally limited to currents not exceeding 500 A and pressures not exceeding 660 V, D.C. or A.C. Oil-break ironclad switches are ordinary oil-break switches (§ 367) in tanks of special mechanical strength. Oil-immersion eliminates the risks associated with open sparking and sometimes makes possible a smaller casing than is required by an air-break switch.

367. **Oil Switches and Circuit Breakers.**—The terms 'oil switch' and 'oil-immersed circuit breaker' have been used indiscriminately in the past, but it is now recognised that the term oil switch should be applied only to non-automatic mechanical devices for breaking currents up to the rated capacity of the switch (§ 371); whereas an oil-immersed circuit breaker is a mechanical device (automatic unless otherwise specified) for breaking the circuit under abnormal conditions such as those of short circuit. The constructional features of both types are described in § 368.

The main advantage of oil immersion is the assistance obtained in quenching the arc which forms when the contacts are separated. The size of the arc is reduced by the cooling effect of the oil and by the hydrostatic pressure which the oil exerts upon the vapour column; also, the head of oil above the contacts forces the insulating liquid between them at the earliest possible moment after their separation. In the case of alternating current the arc is momentarily extinguished as the current passes through zero, and the combined cooling, mechanical, and insulating effect of the oil is generally sufficient to prevent the arc from being struck again. Where direct current is concerned no assistance is obtained from

the form of the current itself (there is no natural recurrent zero in a direct current), hence the arc endures longer than where alternating current is employed. Tests have shown, however, that oil switches and circuit breakers are capable of interrupting direct current under load or short-circuit conditions at the same rating as for alternating current. The oil is soon blackened by carbonisation, but the actual amount of carbon formed is only a small fraction of 1 °/ₒ of the oil after the switch has operated thousands of times, and the properties of the oil, so far as extinguishing the arc is concerned, appear to be quite unaffected. With the use of direct current at 1 500 or 3 000 V for traction purposes there is likely to be an increase in the use of oil switches in D.C. circuits; there is not much inducement to use them in D.C. circuits up to 660 V,* the air-break circuit breaker being quite satisfactory for such pressures, whether direct or alternating. Though air-break switchgear in explosion-proof and flame-proof casings (§ 366) is quite safe for use in explosive atmospheres, it is sometimes more convenient to use oil-immersed switches and, in such services, there is a field for D.C. and A.C. oil switches at all pressures. Probably the principal objection to the use of oil switches in D.C. circuits lies in the high voltage which may be induced when breaking a highly inductive circuit (§ 349). In an air-break switch, even with magnetic blow-out, the circuit is broken less rapidly than in an oil switch, and the inductive 'kick' is therefore lower. The importance of providing shunt discharge paths for the voltage induced in any highly inductive circuit (*e.g.* shunt motor field coils, brake magnet windings, etc.) has already been mentioned (§ 349), and is especially great where oil switches are used.

368. Constructional Features of Oil-immersed Switches and Circuit Breakers.—The main components of any oil-immersed switch are the oil tank; the insulators used to insulate the fixed contacts from the tank; the moving contact or bridge-piece; and the mechanism used to operate the latter (*see also* §§ 343, 372, 373).

The insulators carrying the fixed contacts are generally mounted on the cover of the tank, and for extra high voltage circuits (say

* This has hitherto been about the highest pressure used in D.C. circuits, excepting circuits on the Thury system (§ 317). In the latter, the main (series) circuit is never opened; apparatus is switched 'out' by short circuiting its terminals; the load current is constant and is never broken.

over 33 kV) they are usually of the condenser type.* The terminal stems, connected to the conductors of the external circuit, are led through these insulators and terminate in the circuit contacts of the switch. The moving contact is in the form of a bridge piece which connects the circuit contacts when it is made to bear upon them. Generally the bridge piece is a solid bar or laminated brush of such cross-section that it will carry the heaviest currents which have to pass through the switch without dangerous overheating. Sometimes, however, the bridge piece is of insulating material with a contact piece at each end to engage with the circuit contacts when the switch is closed; the moving contacts are then connected by a fuse or through a series trip coil either of which opens the circuit in event of overload (§§ 342-344, 375). The plane of the circuit contacts is horizontal (except in oil-immersed drum controllers and other special switches) and the bridge piece is raised or lowered, to make or break circuit by means of a rod pass-

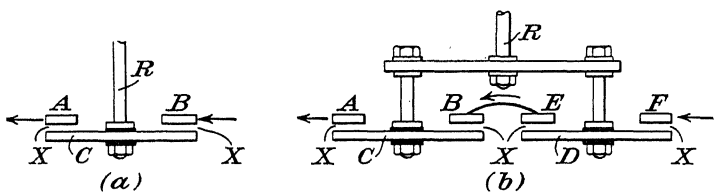


FIG. 76.—Diagrammatic representation of double and quadruple breaks.

ing through the cover of the tank. The operating rod is insulated from the bridge piece by micarta, bakelite, or other suitable material. Generally, the bridge piece, C, Fig. 76 (a), is used in conjunction with two circuit contacts AB; there are then two breaks, XX, in series when the switch opens, and if the rod, R, moves downwards at 5 ft./sec. the total speed of breaking at the contacts is $2 \times 5 = 10$ ft./sec. For extra high voltages two bridge pieces, CD, and four stationary contacts, A, B, E, F, may be used as shown

* *i.e.* built up by alternate concentric layers of dielectric and metal foil, so as to form a number of condensers in series; by suitably adjusting the capacity of each condenser the voltage distribution across the series can be made uniform (§ 289). The pressure gradient in a 'bulk' terminal insulator, consisting of a relatively thick mass of porcelain, moulded composition, etc., is far from uniform and the utilisation of the insulating material is correspondingly inefficient. Condenser bushings are coming into general use for all oil-circuit breakers of large rupturing capacity for pressures of 11 000 V and upwards.

(diagrammatically) in Fig. 76 (*b*); if *R* moves downwards at 5 ft. / sec. the four breaks in series open at a total speed of 20 ft. / sec. Where the upward speed of an auxiliary contact is added to the downward speed of the bridge piece (as in Fig. 78) the total speed of breaking at a quadruple break may be 35-40 ft. / sec.

The circuit contacts are massive blocks if the moving contact is of the laminated brush type (§ 365), or springy clips if the moving element has Vee-shaped knife contacts. In the construction shown diagrammatically in Fig. 77 (*a*), the main, laminated brush contact opens first at *A*, and the arc is struck on the solid copper piece, *B*, which is spring-supported at *S*, makes butt contact with the stationary contact block, and is easily renewable when required. Carbon arcing tips are not suitable for use in oil. In Fig. 77 (*b*) the

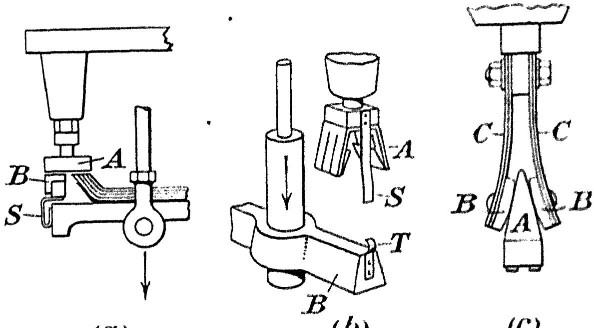
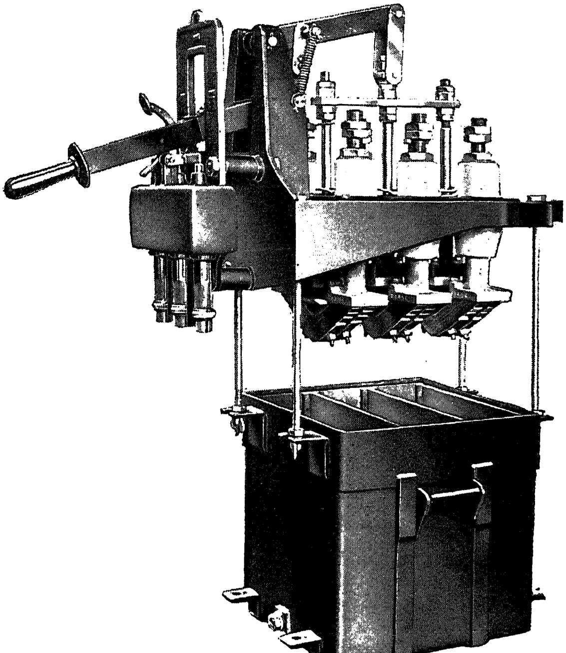


FIG. 77.—Main and auxiliary contacts in oil switches (diagrammatic).

wedge-shaped block, *B*, and the springy fingers, *A*, constitute the main contacts; the auxiliary arcing contacts, *ST*, separate after the main contacts; and by that time the piece, *B*, is moving so rapidly that a 'quick break' is obtained. In Fig. 77 (*c*), the moving contact, *A*, is of narrow triangular section, and is forced between two solid contact blocks, *BB*, which are carried by laminated springy fingers, *C*; arcing contacts (not shown) are fitted as in Fig. 76 (*b*). An ingenious method of increasing the speed of breaking is illustrated in Fig. 78; in the position shown the main butt contacts, *AB*, have separated, but the auxiliary contact, *L*, which is formed as a latch, is drawn down in engagement with the clips, *M*, thus maintaining the circuit through the switch. Meanwhile the spring, *S*, is being compressed by the downward movement of *L*, and when

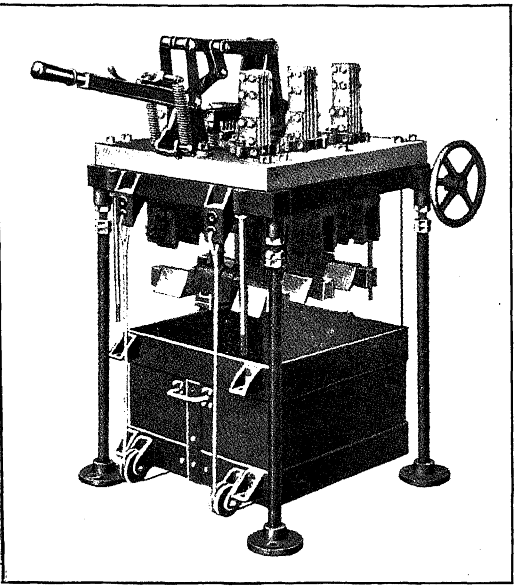


General Electric Co., Ltd. (London).

MEDIUM VOLTAGE, HEAVY CURRENT OIL SWITCH.

The illustration shows the G.E.C. Type IIIA switch (Table 52, § 571) with its tank lowered and the contacts closed. The normal capacity of this switch is 1 000 A at 660 V. A specially long break is provided, and the clearances are on a liberal basis, actually exceeding the requirements of the B.E.S.A. specification. The tank is lined with 5-ply birch which is divided into compartments so that the phases of the switch are separated.

[To face p. 524.



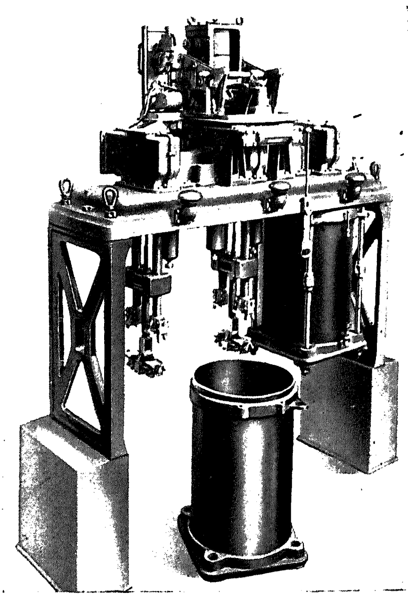
Johnson & Phillips, Ltd.

MEDIUM VOLTAGE, HEAVY CURRENT OIL SWITCH.

This switch is built for rated carrying capacities of 1 500 A and 2 500 A at 650 V. The fixed contacts are of the laminated brush type insulated by a slate base which is supported by the iron framework. An arcing tip is provided on each fixed contact. The tank-lowering gear is operated by the hand-wheel shown. The switch is closed by lifting the handle, engaging the switch mechanism, and pushing the handle downwards. Opening by hand is effected by pressing the tripping lever on the handle. The switch can neither be closed under fault conditions, nor opened slowly at any time. The trip coils are fitted on the front of the board, below the operating handle.

E.H.T. HIGH-POWER OIL CIRCUIT BREAKER FOR REMOTE ELECTRICAL OPERATION.

This circuit breaker is suitable for use on systems up to 35 000 V where an arc-rupturing capacity of over 1 000 000 kVA is required. The fixed contact studs are built on the condenser terminal principle (§ 368) and are strongly braced together at the lower end. The moving contacts are of special design to ensure that good contact is maintained even when heavy fault-current is flowing. Wedge-type renewable arcing tips are employed. The oil tanks are attached to the common cast steel frame by suspension bolts; four small retaining bolts are also fitted to facilitate the removal of the tanks by a combined carriage and lowering device. When the breaker opens on short circuit, clean air is drawn into the air chambers as the oil gases are discharged from the vents. The breaker is normally operated by solenoids but can be tripped by hand if necessary. The closing mechanism is a parallel-motion linkwork fitted on each side of the flexible hinge to balance the closing forces. No live metal is accessible when the breaker is in service, hence no side barriers or protective doors are required on the circuit breaker side of the structure when this unit is used with stonework cubicles. The lead-in connections are in compound-filled boxes and pass through the rear wall to the isolating switch and terminal cells.



Metropolitan-Vickers Electrical Co., Ltd.

[To face p. 525.

the main contacts are 6 or 7 ins. apart, and moving at high speed, the spring withdraws *L* from the clips, and pulls it upwards rapidly. The speed of separation of *L* and *M* is the sum of the upward speed of *L* and the downward speed of *M*. The same figure also shows the shield, *D*, fitted to the lower end of the condenser terminal, *T*, to screen it from the arc; and the smooth-profile corona shields, *C*, which prevent corona discharge from the sharp edges of the contacts.

An important factor in the design of switch contacts is their behaviour under the mechanical forces developed by short-circuit currents. As explained in § 338, the mechanical force due to the field round the conductors of a closed circuit tends to increase the area enclosed by the circuit, hence a laminated brush contact of the type shown in Fig. 79 is subjected to forces, *FF*, which tend to reduce the mechanical pressure at the contacts, and may cause the contacts to become overheated and welded together. With two inverted brushes as in Fig. 80, bearing on an intermediate contact block, *C*, the forces, *FF* (tending to enlarge the circuit), now press the brushes more firmly into contact. The converse action, *i.e.* attraction between conductors carrying current in the same direction (§ 338), causes the fingers *A*, *B* (Fig. 81), to bear more heavily upon the intermediate contact *C*. Contacts which are self-closing under electromagnetic forces are naturally to be preferred.*

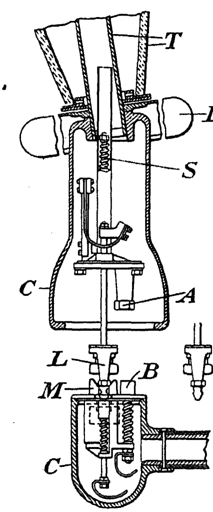


FIG. 78.—Main and auxiliary contacts of Metropolitan Vickers oil-immersed circuit breaker.

In all the cases illustrated by Figs. 77, 78 the circuit contacts are carried by the cover of the switch tank, and the switch is opened by the moving contact or bridge piece travelling downwards from the fixed contacts. This is the usual arrangement, and has the advantage that when the oil tank is lowered the whole

* The three examples cited are reproduced from 'Mechanical and Electrical Effects of Large Currents on H.T. Switchgear,' C. C. Garrard. *Jour. I.E.E.*, Vol. 60, p. 887.

of the switch is accessible for inspection or repair; it must, however, be isolated by an isolating switch (§ 362) before it is touched. Sometimes the circuit connections are made through insulators in the bottom of the tank and the moving element travels upwards to open the circuit; this arrangement has the advantage that the tank is shallower (for a given head of oil over the break) than if the moving contact travels downwards. Also, the moving contact and its operating mechanism can be inspected whilst the live circuit contacts remain submerged; on the other hand, the tank must be emptied before the circuit contacts can be reached and even then they are not easily accessible.

The formation of dangerous switching surges (§ 349) may be prevented by placing 'buffer resistances' in circuit temporarily

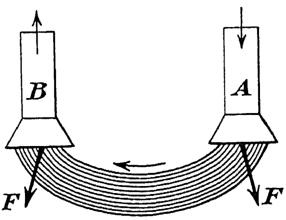


FIG. 79.—The electromagnetic forces, F, tend to open the contacts.

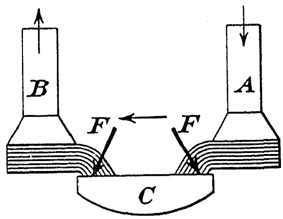


FIG. 80.—The electromagnetic forces, F, improve the contact between the brushes and the block, C.

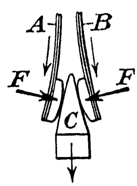


FIG. 81.—Electromagnetic attraction between A and B increases the contact pressure on C.

before the main contacts of the switch close and after they open. This precaution—which renders less sudden the growth or decay of the magnetising current of machines or transformers, or the charging current of cables—may be effected by the use of auxiliary 'charging contacts' on the main switch. Like the auxiliary arcing contacts, the charging contacts make contact before (and open contact after) the main contacts, but the same auxiliary contacts cannot be used both as arcing and charging contacts; for whereas the arcing contacts have to carry the full main current temporarily, the charging contacts are in series with a high non-inductive resistance which acts as a 'buffer' when switching on or off.

If desired, auxiliary switches can be fitted to oil switches so that they open or close relay, signalling or other auxiliary circuits synchronously with the operation of the main switch.

Notes on the operating, tripping, and interlocking mechanism of switches are given in §§ 372, 373, and further information on constructional factors which influence the breaking capacity of oil switches are given in § 371.

369. Air and Oil-Switch Ratings; Current Densities. —The rated capacity of air-break switches and circuit breakers * is the largest current (at rated frequency in the case of A.C.) which they will carry continuously under the required conditions of service without exceeding 30° C. temperature rise (20° C. rise in the case of switches rated below 100 A), the temperature of the surrounding air being not higher than 40° C. When determining this temperature rise: (*a*) For switches of 2 000 A or lower rating —the connecting cables should be operated at a current density conforming with Table 40 (§ 280) where this is applicable; or should be copper straps run at 1 000 A / sq. in. (*b*) For switches rated above 2 000 A—the connections should be such that the temperature rise in them is not less than 80 % or more than 100 % of the rise permitted in the switch. The object of these clauses is to eliminate abnormal heating or cooling of the switch by thermal conduction from or to the connecting leads. The permissible temperature rise (measured by thermometer) in tripping, closing, and blow-out coils under service conditions is 50° C. for cotton, silk, paper, etc., impregnated and for enamelled wire; and 70° C. for micanite, asbestos, and bare coils.

The carrying capacity or rated current of an oil switch or oil-circuit breaker is the heaviest current (at rated pressure and frequency) which it will carry without the temperature rise (at the hottest part of the oil or at any part of the switch outside the oil) exceeding 30° C. (40° C. for switches or circuit breakers rated above 2 000 A) above an air temperature not exceeding 40° C. (or 80° C. total temperature if the air temperature exceeds 40° C.). The provisos made in the preceding paragraph regarding current density in connections are applicable here also.

A complete statement of the rating of an oil switch or oil-circuit breaker includes the carrying capacity in amps., the rated

* The notes in this paragraph are based upon B.E.S.A. Reports, Nos. 109, 110 (Air-break Knife Switches, Laminated-brush Switches, and Circuit Breakers, for not higher than 660 V; excluding totally enclosed and flame-proof types), but the actual specifications should, of course, be consulted when the precise terms and conditions are of importance.

voltage and frequency, and the breaking capacity in kVA (§ 371). The current rating may be increased as the frequency decreases, and must be decreased as the frequency increases, by an amount which depends upon the design of the switch; in a particular case, a switch rated at 600 A, 50 cycles was rated at 800 A, 25 cycles. The highest standard voltage rating at present contemplated in this country for oil switches is 165 000 V, but switches can be built for higher voltages if required.

The maximum permissible current densities in the various parts of a switch or circuit breaker are those which are consistent with the temperature rises specified above, and which permit the switch to operate indefinitely without undue deterioration of the contacts. Many factors bear on these points, hence it is impossible to give definite figures for the current density; but as a general guide it may be taken that 600-1 000 A / sq. in. of section is permissible in connections, switch blades, and bridge pieces, the lower value being used for currents of 3 000 A or over; whereas 75-100 A / sq. in. of contact surface is a reasonable allowance where spring clips and blades are concerned, rising to 400 or 600 A / sq. in. of contact surface in the case of contacts subjected to high mechanical pressure (by bolting or by toggle mechanism etc.). All contact surfaces should be formed on relatively heavy masses of metal in order that the contacts may have considerable capacity for heat; this greatly affects the breaking capacity of the switch (§ 371).

370. **Breaking Capacity Required in Circuit Breakers.**— The breaking (or rupturing) capacity of an oil switch or circuit breaker is the maximum kVA which it will interrupt at rated voltage. It is given numerically by the product $nEI/1\,000$; where E = rated voltage; I = the actual current *at the moment of separation of the contacts;* and $n = 1$ for single-phase, 2 for 2-phase, and 1·732 for 3-phase systems respectively. The most severe conditions under which a circuit breaker can be required to act are those of short circuit. As explained in § 339 it is not easy to calculate accurately the current flowing under short-circuit conditions, and in the case of circuit breakers, the problem is further complicated by the fact that the current to be determined is that which is flowing at the moment of separation of the contacts. If the contacts opened instantaneously on the occurrence of a short circuit they might be called upon to break 10 or even

20 times the total rated kVA of the generators connected to the system (§ 339); if, however, the contacts open $\frac{1}{5}$ sec. after the incidence of the short circuit they will not be required to interrupt more than, say, 6 times the total rated kVA capacity of the generators feeding the fault (assuming the generator reactance to be 10 %; *see* § 340); whilst if the opening of the contacts be delayed for, say, $1\frac{1}{2}$ secs. by an artificial time lag, the current to be broken will probably be that corresponding to about 3 times the rated kVA capacity of the generators, *i.e.* it will be the steady short-circuit current of the system.

The current flowing at the circuit breaker *S* (Fig. 82) is limited

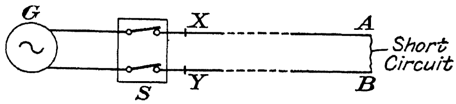


FIG. 82.—Short circuit at the far end of a feeder connected to a single generator.

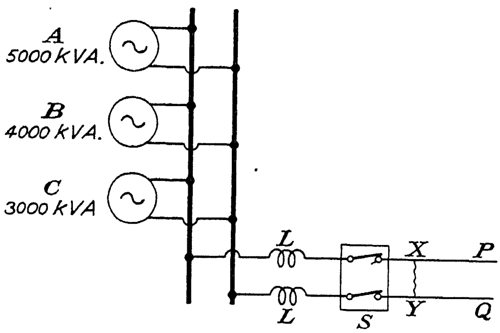


FIG. 83.—Short circuit on a feeder connected through reactance coils to several generators in parallel.

by the reactances and resistances in the complete circuit, *GABG*, between the generator and the short circuit, including the reactance of the generator itself. In the case of a circuit breaker at a power station, maximum current flows when the short circuit is at *XY* (Fig. 82) immediately beyond the switch. The reactance in circuit is then only that of the generator plus that of any protective reactance (§ 340) or transformer which is connected between the generator and the circuit breaker.

Suppose that the rated capacity of the generator is 10 000 kVA, that the generator reactance is 10 % (*i.e.* reactance drop at full load = 10 % of normal

voltage, *see* § 340), and that the external reactance is 4 °/
kVA at the moment of short circuit = 10 000 / ($\frac{10}{100}$ +
The kVA to be interrupted by the circuit breaker, assumi
fallen to 0·6 of its initial value by the time the contacts o
42 860 kVA.

Even in such a simple case as that consid
ing example there is considerable latitude for
because it is necessary to assume the extent to
will have decreased at the moment of openin
the extent to which the voltage is lowered as a
circuit. For example, if there be high extern
delays the demagnetising of the alternator fiel
current may still be 75 °/₀ of its initial value
circuit breaker (in the example chosen) m
0·75 × 71 430 = 53 500 kVA. A considerabl
essential to allow for this uncertainty, and fo
normal pressure surges, resonance, etc.

In practice it is often difficult to determine
ance of a short-circuited system (upon which
value of the short-circuit kVA). The general
may be illustrated by considering a short-circu
immediately beyond a circuit breaker, *S*,
through reactances, *L*, to bus bars on which thr
C, are connected in parallel. These generators
respectively, of 5 000, 4 000, and 3 000 kVA r
12 000 kVA. The total current flowing at
kVA at rated voltage) could be calculated by
bar voltage to be applied to a total reactance of (
a = total reactance of the two coils *L*; and *b*
ance of the three generators in parallel. S
reactances of generators, reactance coils, feeder
expressed as percentages (*see* § 340) it is sim
basis, but it must be remembered that the 'pe
of any machine or circuit is referred to *its ow*
if the actual load is greater, the percentage re
creased in the ratio of the actual load to th
following example will make this clear * :—

* For many other examples of short-circuit calculati
plicated networks, the reader may be referred to an excelle
in the *Metropolitan Vickers Gazette*, June, 1921.

The total kVA capacity on the bus bars in Fig. 83 is 12 000 kVA, and if the reactance of generator A is 10 % (based on its own rating of 5 000 kVA) it is (12 000 / 5 000) × 10 % = 24 % with reference to the bus bar kVA. Similarly, if the reactance of B be 8 %, and of C be 12 %, their reactances referred to 12 000 kVA are (12 000 / 4 000) × 8 % = 24 %, and (12 000 / 3 000) × 12 % = 48 % respectively. Adding the reciprocals of these reactances we have $\frac{1}{24} + \frac{1}{24} + \frac{1}{48} = \frac{5}{48}$ which is, itself, the reciprocal of the equivalent reactance of the three generators in parallel. Thus, referred to the bus bar capacity of 12 000 kVA, the effective reactance of the three generators is $\frac{48}{5} = 9{\cdot}6$ %. Again, if the total reactance of the two coils, L, be 5 % on a 5 000 kVA rating, it is (12 000 / 5 000) × 5 % = 12 % with reference to 12 000 kVA. Under these conditions the initial kVA at the short-circuit = 12 000 × 100 / (9·6 + 12) = 55 000 kVA. As the total reactance in circuit is rather high (21·6 %) it may be assumed that the kVA to be interrupted when the contacts open in $\frac{1}{5}$ sec. is 0·7 × 55 000 = 38 500 kVA.

For a switch at position S (Fig. 83), there is always a possibility of a short circuit at XY, close to the switch, hence this condition should be assumed when calculating the breaking capacity required, but for a switch at the far end of the lines PQ, the reactance and resistance of the latter must necessarily be between the switch and the power station and should therefore be included in the calculation, the percentage reactance of the line with reference to its own rated capacity being increased to correspond to the bus bar kVA as in the preceding paragraph. The calculation of the actual reactances of cables and overhead lines (from which the ‘percentage reactance’ at once follows) is discussed in Chapter 14.

In the case of a short circuit at the far end of a line, the impedance of which is high compared with that of the generators, the kVA to be interrupted is determined almost entirely by the impedance of the line, and it may then be assumed that the bus bar voltage remains constant, so that the kVA to be interrupted is equal to the initial kVA and is given by (Rated kVA of line × 100 / Percentage impedance of line). If, however, the line impedance be low compared with that of the generators it is necessary to allow for the impedance of both; and in this case the kVA to be interrupted is, say, 75 % of the initial kVA owing to the fall in voltage caused by demagnetisation of the generator field.

For example, suppose that a feeder rated at 1 000 kVA has 3 % reactance and 4 % resistance (referred to its own rating in both cases) and suppose that this feeder is connected to a 3 000 kVA station in which the generator reactance is 10 %. On the basis of 3 000 kVA, the feeder reactance is (3 000 / 1 000) × 3 % = 9 %, and its resistance is (3 000 / 1 000) × 4 % = 12 %. The total reactance is thus (9 + 10) = 19 % and the resistance (neglecting that of the generator) is 12 %. The percentage impedance is therefore $\sqrt{[(12)^2 + (19)^2]} = 22{\cdot}5$ % and the kVA to be interrupted is 0·75 × (3 000 × 100 / 22·5) = 10 000 kVA.

In the absence of definite information it is usually safe to assume that the 'short-circuit reactance' of a modern alternator is 10 % and that of a transformer about 4 %, reckoned on the rated capacity of the generator or transformer as the case may be. The 'short-circuit reactance' may be less than the reactance under conditions of normal magnetic flux density and is equal to $(100 / x)$ %, where x = Current on dead short circuit at rated voltage / Rated full-load current (§ 340).

Though the methods explained above provide a convenient means of estimating the kVA to be interrupted, the duty actually required from the switch varies widely according to the point in the voltage wave at which the short circuit is established, and according to the point in the current wave at which the contacts are separated.

371. **Factors Determining Breaking Capacity of Oil Switches.**—The breaking capacity (kVA) to be provided in a circuit breaker may be calculated approximately as explained in the preceding paragraph, and it is usual to require that the circuit breaker should be capable of interrupting the kVA thus calculated twice in rapid succession, and thereafter be at once capable of carrying normal full load. The principal factors influencing the breaking capacity of an oil switch are: (i) The form and mass of the contacts, and the mechanical strength of the switch components. (ii) The speed of breaking contact, the number of breaks in series per phase, and the total length of break per phase. (iii) The clearance between phases and between live metal and earthed metal (the tank) below oil and in air. (iv) The volume of oil in the tank and the head of oil over the contacts at the moment of opening; and the suitability of the oil employed. (v) The amount of air space above the oil and the efficacy of the vents for the discharge of oil vapour. (vi) The mechanical strength of the tank and its supports.

The contacts must be massive to prevent their attaining a dangerously high temperature during the arcing period, and thus to lessen the amount of metal vaporised. The contacts should not be forced apart by electromagnetic forces (§ 369) and no conductor in the switch should be capable of deformation by the mechanical forces developed under short-circuit conditions (§ 338).

A quick break reduces the heating of the contacts at the moment of separation, thus reducing the stability of the arc, and extinguishes the arc more rapidly, thus reducing the volume of vapour produced. Other factors being equal the arcs at a multiple gap are less stable than the corresponding arc at a single gap; and the

greater the total length of break, the less chance there is of the arc persisting. The disposition of the conductors in some oil switches is such that there is a magnetic blow-out effect (§ 365).

The clearance from phase to phase, and between phases and earthed metal is always of importance as regards insulation under normal conditions; and it is of special importance when the contacts open under excessive load, because the arc may produce a short circuit between phases or to earth if the clearances be not ample. Barriers of insulating material between phases and insulating linings in the tank reduce this risk: the barriers may be of 3- or 5-ply non-resinous wood (birch or maple); resinous wood is apt to cause the contacts to become foul and possibly cause sticking. For pressures above 6 600 V (or at lower pressures if the current be heavy, say, 1 000 A or over) the circuit breaker for each phase is often placed in a separate tank; the single-tank construction is sometimes used, mainly on the Continent, for 33 000 V switches of small rupturing capacity.

A large volume of oil in the tank prevents the oil from being heated to a dangerous temperature (§ 369) and a considerable head of oil is required above the point of rupture in order that there may be sufficient hydrostatic pressure to compress the vapour column of the arc and to drive oil forcibly between the contacts; also, in order that no incandescent gas or vapour may escape from the oil. The air space above the oil in the tank acts as a buffer, and it must be vented, by pipes leading away from any place where oil vapour would be dangerous, so that vapour can escape easily but so that no oil can be driven out by the explosive action of the arc.

The general requirements to be fulfilled by oil for use in switches are stated in § 77 (1). Where oil switches are exposed to severe cold it is usual to provide thermostatically controlled electric heaters in the oil tank to prevent the oil from becoming so viscous that it no longer performs its functions properly.

The oil tank is generally constructed of sheet steel or boiler plate with welded joints, or of solid drawn steel. If the switch is to be of large rupturing capacity, the tank should be capable of resisting an internal pressure of 500-700 lbs. / sq. in.; and the cover and the attachments between tank and cover must be equally strong. Unsupported flat surfaces must be avoided in the tanks and where necessary the tank must be reinforced by rolled steel bands or by a cage of angle or channel irons and tie rods. In large, high-voltage, outdoor switches, the tanks usually stand on the floor; arrangements should then be made to ventilate the bottom of the tanks to prevent rusting. In large switches, the tank dimensions are sometimes 5 or 6 ft. dia. × 7 or 8 ft. high. For all but low and medium voltages comparatively slight modifications are sufficient to render oil-circuit breakers suitable for outdoor service, thus saving the cost of buildings.

An explosion chamber in the form of a small cylindrical chamber open at the bottom is sometimes placed round each circuit contact of a circuit breaker. This chamber confines the arc, and is capable of resisting an internal pressure of 700-1 000 lbs. / sq. in. The vapour formed by the arc is driven downwards and in escaping it drives oil from the chamber on to the receding contacts, thus helping to cool them.

Table 52 gives leading particulars of standard oil-break switches by the General Electric Company (London), and will repay a careful study. Oil-circuit breakers for higher voltages and for higher breaking capacity are of course available if required up to, say,

600 A carrying capacity at 115 kV and 400 A at 155 kV, with breaking capacities up to 1 500 000 kVA. Though the current-carrying capacity of a switch is greater at lower frequencies (§ 369), it is probable that the breaking capacity is greater at 50 cycles than at 25 cycles / sec., the current passing through zero more frequently and the energy developed per half-cycle being less at the higher frequency.

TABLE 52.—*Breaking Capacity of Oil-Break Switches.* (*By Courtesy of the General Electric Co., Ltd.*).

Type.	Maximum Breaking Capacity.*	Carrying Capacity. Volts.	Carrying Capacity. Amperes.	Total Break.	Head of Oil.	Volume of Oil. Gals.	Volume of Oil. Cu. Ins.	Weight Without Oil.	Operation. D = Direct E = Electrical.
	kVA.	V.	A.	Ins.	Ins.	Gals.	Cu. Ins.	Lbs.	
I	15 000	3 300	100	4	5	3	860	126	*D*
II	30 000	3 300	200; 300	4	5	$4\frac{1}{2}$	1 300	168	*D*
IIA	30 000	660	400; 600	$4\frac{1}{4}$	$3\frac{1}{2}$	$4\frac{1}{2}$	1 300	174	*D*
III	52 000	3 300 6 600	400; 600 200; 300	$4\frac{5}{8}$ 6	6 5	8	2 280	230	*D*
IIIA	52 000	660	800; 1 000	$5\frac{1}{2}$	4	8	2 280	240	*D*
IV	100 000	3 300 6 600 11 000	1 000 600 100	7	$6\frac{1}{4}$	15	4 200	290	*D* or *E*
IVA	100 000	660	1 200; 1 500 2 000; 2 500	$7\frac{1}{2}$	$5\frac{1}{4}$	15	4 200	340	*D*
IVT	125 000	3 300 6 600 11 000	800; 1 000 400; 600 100	$7\frac{1}{2}$	8	17	4 750	480	*D* or *E*
VT	200 000	11 000 22 000	200; 400 200	10	10	39	11 000	560	*D* or *E*
VIT	350 000	3 300 11 000 22 000 33 000 †	300; 600; 1 000; 2 000 300; 1 000 200; 300; 600 200	12	11	66	15 000	2 200	*E*
VIIT	800 000	33 000	200; 400	20	14	150	42 000	5 376	*E*

372. Operating and Trip Mechanism of Switches.—In the simple isolating and knife switches we have merely a pivoted blade

* Here calculated as (Current flowing *at the instant of rupture* × Normal voltage between phases × $\sqrt{3}$ / 1 000). The switches are suitable for use with an instantaneously acting release on a total generator capacity = $\frac{1}{8}$ of the breaking capacities given. The factor of safety of the switches under these conditions is greater than 2, thus allowing sufficient margin to deal with the instantaneous short-circuit current should this coincide with the instant of rupture of the current.

† With neutral earthed; these switches may only be used up to 22 000 V if the neutral is insulated.

which is turned about its pivot and pushed into (or pulled out of) engagement with the stationary contacts, either by means of an insulating handle on the blade or by rotating a square shaft which acts as the pivot for the blade. In oil switches, where a contact bridge piece of the blade type has to be moved perpendicularly to or from spring clip contacts, the bridge piece is carried by an operating rod which is pulled up (to close the switch) by a bell crank mechanism, against the control of powerful springs. Power to close the switch is applied by hand (generally near the switch but sometimes at the far end of a series of bell cranks and rods if remote control is desired) or by means of an electromagnet. In either case the mechanism is designed so that a convenient force and moderate displacement at the point of application of the power, give the desired movement of the contacts and a suitable pressure between the closed contacts. It is necessary to provide not only for suitable pressure between the contacts (which pressure must be high where laminated brushes are used) but also for the compression of springs which are powerful enough to open the switch rapidly; in the case of blade and spring clip contacts the operating springs must be powerful enough to overcome the friction between the contacts and still leave a net force sufficiently great to accelerate the moving parts rapidly. Any switch which is required to open automatically, in the event of predetermined abnormal conditions, must be provided with some form of latch, the opening of which leaves the moving system free to be displaced by the compressed operating spring; also, the operating handle must be "free" in the sense that the switch cannot be held closed if the circuit conditions are such that the trip mechanism operates. The force required to close the switch and the force stored in the compressed spring ready to open it are of considerable magnitude, especially in heavy current switches with laminated brushes; and, while it is necessary that the closing force should normally exceed the opening force, it must be arranged that a relatively small tripping force will release the mechanism. In this connection the toggle mechanism is particularly useful.

Referring to Fig. 84, the laminated brush, A, is pressed on to the contacts, BC, by the linkwork, DEF, which is so designed that when it is moved to the right from the dotted position *a*, *b*, the rod, D, is moved vertically upwards. The pressure between A and BC is a maximum when the links, EF, are in line with D, but this position is unstable, so the mechanism is pushed over until the links, EF, rest against stops, XY. The pressure between the contacts is still considerable, but the

resultant force at G is relatively small hence application of a relatively small force opposed to G will bring the links first to the vertical position and then to the left of it thus 'breaking' the toggle and allowing a compression spring (not shown) on the spindle, D, to open the contacts rapidly.

If A bears upon each contact, B, C, with a force of 50 lbs. the total thrust in D (see enlarged diagram of forces, Fig. 84) is 100 lbs. The thrust in E = 100 / cos $2\frac{1}{2}°$ = 100 / 0·999 = 100·1 lbs. = thrust in F. The resultant of the thrusts in E and F = 2 × 100·1 × sin $2\frac{1}{2}°$ = 8·73 or, say, $8\frac{3}{4}$ lbs. If a pull, H, greater than $8\frac{3}{4}$ lbs., be applied as shown, the apex of the toggle will move to the left and the toggle will be 'broken.' So long as the links, EF, are to the right of the vertical, against the stops, the mechanism is stable.

The valuable property of this mechanism is that a small lateral (closing) force is sufficient to produce a high pressure (lb. / sq. in.) between the contacts, whilst an equally small (tripping) force is sufficient to release the mechanism.

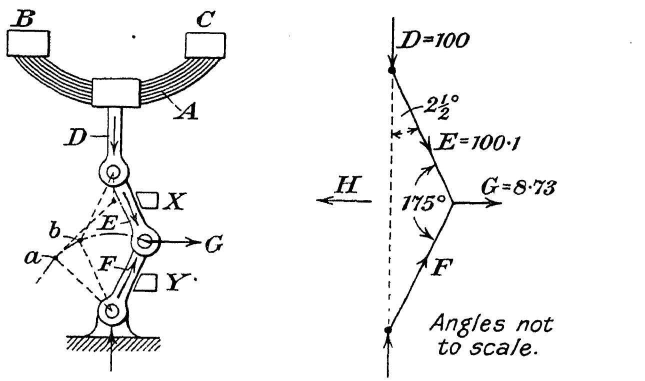


FIG. 84.—Diagrammatic representation of toggle mechanism.

Manual operation is simple and convenient in the case of small and medium sized switches, the whole switchboard occupying comparatively small space and the connecting linkwork between the operating handle and the switch being light and easily manipulated. Where high power, high voltage switches are concerned, however, it may be necessary to place the switches some distance away from the control board in order that the switches may be housed safely and conveniently, and in order that the control board for the whole of a large plant may be reduced to conveniently small dimensions. Switches may be operated by hand from a considerable distance through a series of rods (or steel tubing) connected by bell cranks where required, but this system of remote control does little to reduce the dimensions of the control board; moreover, it demands increased physical effort on the part of the operator. In such cases electrical remote

control offers obvious advantages; * the switch is closed by aid of a closing solenoid and plunger under the control of a simple press button on the operator's master-switchboard. With another method, the closing button starts a servo-motor which compresses or stretches a spring; when fully 'loaded' the latter is released, thus closing the main switch. Low voltage D.C. (say 100 V) is used for the closing solenoid or motor. It should be arranged that if the switch is tripped automatically directly it is closed (as when it is closed on a fault), the closing button has to be pressed again before the closing coil will again operate; this is the equivalent of the 'free handle' mechanism and prevents the closing coil and trip coil from closing and opening the switch repeatedly.

By arranging the linkwork (between the operating rod and the contact-carrying rod) inside the switch cover a 'clean' design is obtained and the linkwork is protected. Wherever possible the springs which open the switch should be in duplicate; each should be capable of operating the switch without the help of the other, and there should be no tendency for the mechanism to 'bind' in the event of one spring breaking. Current must never be passed through a spring †; if there is any risk of this occurring the spring should be short-circuited by a flexible lead or auxiliary contact pieces.

---

* An extreme example of the possibilities of electrical remote control of switches is to be found in the 'Handyell' system of remote switching on supply station networks without the use of pilot wires or special cables. Each of the switches to be controlled is provided with a device consisting of a magnet coil and a condenser which are connected permanently in series across the supply mains. At the normal voltage and frequency of the system no appreciable current flows through this operating device, but when a ripple of frequency corresponding to the tuning of the relay on the switch to be operated, is sent out from the central station through the ordinary supply mains, a current flows by resonance (§ 47) in the relay circuit and the main switch at that point is operated. The controlling ripples are produced by an auxiliary motor-generator and may be of any frequency from, say, 200 to 500 cycles / sec.; they do not affect the ordinary supply in the least, are applicable to D.C. or A.C. systems, and are transmitted effectively through transformers and miles of underground cable. Transient disturbances due to short circuits, surges, etc., do not affect the tuned relays, and any number of switches can be controlled selectively by varying the frequency of the controlling ripples.

† Apart from the danger of the spring being heated and softened by current passing through it, the mechanical attraction between turns when carrying current (§ 338)—increases the pull of a tension spring, and reducing the thrust of a compression spring—may prevent the spring from acting at the desired moment or in the desired manner.

Whatever the type of switch and closing mechanism, the tripping mechanism operates by leaving the moving contact of the switch free to be withdrawn from the fixed contacts by the spring or springs provided for the purpose. This may be done by 'breaking' a toggle mechanism or otherwise removing restraint from the switch contact-piece by releasing a latch of some kind, at some point in the mechanism which normally holds the switch closed. This latch may be released by the movement of the plunger of a trip-solenoid or by the buckling of expansion strips which carry the main current and release the switch in the event of sustained overload. A thermally-operated tripping device of this type has an inverse time element (§ 344) and has been applied successfully to air-break circuit-breakers of carrying capacities from 15 to 250 A, at low or medium pressures, D.C. or A.C.

In order that a mechanical trip gear may be actuated by the plunger of a low-power trip coil (the latter being excited by any one of a number of relays, § 344) it may have to be in the form of a multiple lever so that a small force at the plunger exerts considerable force at the actual point of tripping. The mechanical details of trip mechanisms vary greatly and need not be described. The main essentials are that the gear should be sensitive without being liable to operation by vibration; and that it should be capable of accurate adjustment and free from slackness or sticking. Hard steel inserts reduce wear at the trigger and latch, and brass sleeves and washers prevent 'rusting up.' If it is arranged that the switch is always opened (whether deliberately or automatically) by means of the trip gear, the latter is kept in free working order. The tripping mechanism should always be at the switch, so that the mass of moving parts to be accelerated by the springs which open the switch is reduced to a minimum, but it should be so placed with regard to the live parts that it can be inspected and adjusted whilst the switch is in service.

The British standard limits of operation for closing and tripping coils, low-voltage, overload, and reverse devices for air- and oil-break circuit breakers are given in Reports Nos. 110 and 116. Sometimes the overload trip coil can be actuated directly from the main circuit (through a current transformer, § 108, if necessary), but the advantage of controlling the tripping by relays is that the latter are built as precision instruments and therefore make

possible very accurate control. Overload and low voltage tripping are the minimum automatic features which should be provided on circuit breakers, and there is no difficulty in applying also reverse power, leakage, and various selective systems of protection (*see* Chapter 15).

The time elapsing between the incidence of a short circuit or other fault and the opening of the main circuit breaker is an important consideration. As explained in § 344 a definite or an inverse time lag may be introduced deliberately in the action of the relay, but in the case of an oil-immersed circuit breaker intended to open 'instantaneously' on short circuit, the relay closes and the trip coil is fully energised within say 0·1 sec., and the main contacts are separated within say 0·2 sec. from the incidence of the short circuit. The arc is generally extinguished in less than 1 cycle (*i.e.* less than 0·02 sec. in the case of 50-cycle A.C.) after the arcing tips separate and in no case should it persist for more than a few cycles. The moving parts of the switch are accelerated, moved to the end of their stroke, and brought to rest in less than 1 sec., and in order that there may be no violent mechanical shock at the end of the stroke, the moving parts are generally brought smoothly to rest by arranging that the tubular guides act as dashpots, or by equivalent means.

D.C. generators and rotary converters, particularly those supplying high voltage direct current (*e.g.* 1 500 V or 3 000 V for traction), are liable to flash-over on the commutator in the event of a short circuit on the D.C. system. It has been found that such flashing-over can be prevented if the generator or converter is protected by a circuit breaker capable of operating and reducing the current below the flashing value in less time than is required for a commutator bar to pass from one brush arm to the next. A standard air-break circuit breaker may operate in about 0·1 sec. but, by eliminating mechanical trip gear and reducing the inertia of the moving parts, high-speed circuit breakers have been developed which operate in 0·005-0·01 sec. These circuit breakers are effective in preventing flash-over on dynamo or converter commutators, but such rapid operation is undesirable in A.C. circuit breakers because it would increase the shock to the system and increase the breaking capacity required in the circuit breaker without effecting any useful purpose.

373. Interlocks and Indicating Devices.—Mechanical and

electrical 'interlocks' are of vital importance in the safe manipulation of electrical switchgear, and they are used in an endless variety of forms. Whilst the details may be modified to suit any requirements, the principles involved are few and simple. As an example of mechanical interlocking, a switch handle may be provided with an extension piece or coupled to a rod which acts as a bolt, making it impossible to open the cover or enclosure of the switch until the switch handle is 'off'; and equally impossible to put the switch handle into the 'on' position until the cover or enclosure is closed. Again, interlocking devices similar to those used in a railway signalling-frame may be employed to ensure that certain switches are not closed simultaneously, or that switches are closed only in a predetermined sequence. The latter function is easily performed by electrical interlocking, it being then arranged that switch A closes a circuit which must be closed before switch B is unlocked or operated automatically (by a solenoid), as the case may be. In draw-out type switchboards (§ 380) it is made mechanically impossible for any parts to be 'live' whilst they are accessible.

It is generally evident by inspection whether an open-type, manually operated switch is 'off' or 'on,' but wherever the switch is concealed or enclosed it is necessary to have a definite indication of its position. This may be provided by attaching 'on' and 'off' labels to the operating handle in such a way that only the appropriate legend is visible through an aperture provided for the purpose. Red and green lamps (or preferably plain lamps behind red and green lenses) are used extensively to indicate the setting of a switch, auxiliary circuits being arranged so that the red light is shown when the switch is 'on' and the green light when it is 'off.' It is becoming increasingly common to provide switchboards with key diagrams made on translucent glass and provided with lamps interlocked electrically with the main switchgear so that the actual circuits completed are illuminated from the back of the diagram.

A complete system of automatic indicators and alarms is very necessary where the switchgear is remote-controlled. Audible alarms (bells or hooters) may be given automatically in the event of circuit breakers opening, lightning arresters operating, overheating in bearings, or interruption or other irregularity in the supply of ventilating air, circulating water, etc. One alarm may

be common to all these causes, discrimination being effected by an annunciator similar to that used in ordinary bell-circuits.

A red lamp and audible alarm are desirable to indicate failure in a potential circuit (voltmeter or wattmeter pressure circuit) due to blown fuses or broken leads.

374. **Special Switches.**—An important type of switch not hitherto mentioned is the 'faceplate' type, as exemplified in the majority of motor starters, Chapter 29. In this type of switch, which is also much used for selecting instrument circuits, a series of circuit-contacts are mounted on an insulating baseplate and a moving contact (generally of the laminated brush type) is moved parallel to the baseplate (either on the arc of a circle or along a guide rod) so as to touch the appropriate contact stud or studs. There is considerable friction between the moving and fixed contacts if the dimensions and bearing pressure are sufficient to permit heavy currents to be carried safely. Except for weak current circuits this type of switch is not suitable for interrupting current as a 'quick break' in the accepted sense of the term is not possible. To eliminate arcing on the contacts of a faceplate motor starter it is often arranged that the current is always interrupted at a 'contactor' in the circuit. The term 'contactor' is applied to switches (air break or oil-immersed) which are capable of breaking a load current and which are operated electromagnetically—especially in connection with the control of motors. For currents up to 500 or 600 A, the moving contact is generally solid and arranged to give a rolling motion on the fixed contact as the contactor closes or opens. In heavy-current contactors, or medium-current contactors which have to carry full load for long periods, the moving contact is of the laminated-brush type (§ 365) and may be moved on a straight line perpendicular to the plane of the fixed contacts by the action of a solenoid, or it may be moved on the arc of a circle by means of a bell-crank mechanism. Air-break contactors are used largely for the control of traction motors, and for motors in heavy industrial service, generally for pressures not exceeding 660 V but sometimes for pressures up to 3 300 V, three-phase. There is no basic distinction between contactors and circuit breakers (air-break or oil-immersed, as the case may be).

Switches differing indefinitely in details of mechanical construction and electrical connection are used for 'multi-way' switching. A few typical methods are illustrated diagrammatically in Figs.

85-90; some special switches used in the control of lighting circuits are described in Chapter 21; and various types of motor starters are described in Chapter 29.

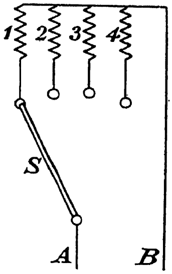


FIG. 85.—Single-pole multiway switch selecting one of several loads.

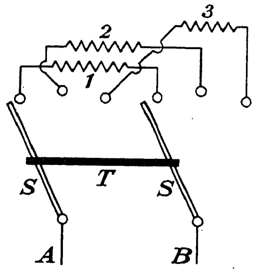


FIG. 86. — Double-pole switch selecting one of several loads.

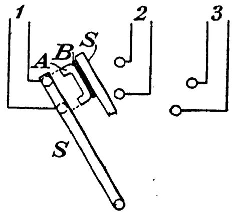


FIG. 87.—Switch closing one of several independent circuits (*cf.* Fig. 90).

In Fig. 85, the pivoted switch arm, S, connects A to one terminal of any one of four loads 1, 2, 3, 4; the other terminals of the latter being permanently connected to B. For purposes of isolation there must be a double-pole switch between AB and the supply.

In Fig. 86 the two switch arms, S, coupled mechanically by the insulating

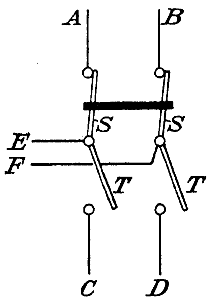


FIG. 88.—Double-pole change-over switch.

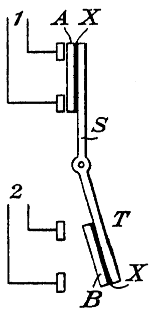


FIG. 89. — Change-over switch closing either of two independent circuits.

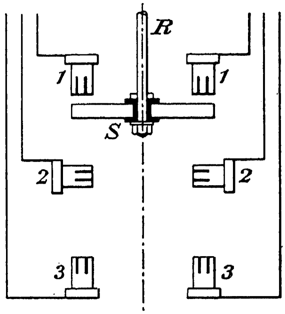


FIG. 90.—Switch closing one of three circuits (*cf.* Fig. 87).

piece, T, connect the supply leads, AB, to any one of the loads 1, 2, 3. In this case the load circuits are electrically independent and, if SS has an 'off' position, it can serve as the double-pole switch between the mains and the load circuits.

The switch arm, S, in Fig. 87, is a purely mechanical device. It carries the contact-bridge, A (from which it is insulated at B), and this bridge closes any one of

three circuits 1, 2, 3 which are electrically independent and may have different sources of supply.

The double-pole switch, SS, Fig. 88, has extension blades, TT (at say 135° with SS) so that the leads, EF, can be connected either to AB or to CD, according to whether the switch is closed in the up or the down position. In some cases a single pair of blades, SS, is swung through 180° to effect the alternative connection. By either method only one of the two connections can be made at once.

In Fig. 89 the arm, ST, carries insulated contact-bridges, AB, which close *either* circuit 1 *or* circuit 2 (*cf.* Fig. 87). Similarly, in Fig. 90, the switch blade, S, is moved by the rod, R, along the dotted axis to close any one of three circuits (possibly electrically independent) which are connected to the contacts 1, 1; 2, 2; and 3, 3.

The 'drum controller' (*see also* Chapter 29) is a development of the principle illustrated in Figs. 87, 89, and 90, a spindle carrying contact-segments being rotated about an axis parallel with a row of contact-fingers between which the segments effect any desired sequence of connections.

Typical of switches which are 'special' in the method by which they are operated, rather than in the switching which they perform, are time switches (operated by a clock), and current-limiter switches which open circuit or produce a flicker when the demand of a circuit exceeds a predetermined value (§ 272).

375. **Fuses.**—The protective action and rating of fuses has already been discussed in § 342. The simplest mounting for a fuse is between two terminals (on an insulating base) to which are connected the circuit wires on each side of the fuse. Such an 'open' fuse wire is, however, very dangerous; when the fuse 'blows' molten metal may injure a bystander or start a fire. The fuse should be so cased in and arranged that its melting causes no damage to the surroundings. Small fuses for house-lighting circuits * are commonly mounted between brass terminal plates which are carried by a porcelain block and separated by a porcelain partition round or through which the fuse wire is threaded; the whole is enclosed by a screw-on porcelain cover. Before renewing such a fuse, the switch controlling the circuit must be opened, otherwise, if the fault be still present, the new fuse will blow directly it completes the circuit and may seriously injure the operator. This risk is eliminated by mounting the fuse in a porcelain tube which is provided with a terminal block at each end; these blocks make contact with spring clips on an insulating base, the clips being connected to the circuit wires. The porcelain tube is shaped externally as a hand-grip or handle

* Seldom used now, as all fuses are concentrated in the distribution boards, see Chapter 22.

and, to renew the fuse, the porcelain carrier must be withdrawn completely from the live terminals ; even if the fuse blows directly the carrier is replaced in the clips, the porcelain tube protects the operator from injury. The carrier can be formed with a hood at each end to cover the live clips and make it impossible for the operator to touch the latter when removing or replacing the carrier.

The totally enclosed or cartridge fuse is similar to the porcelain tube type in general construction but the tube is of fibre or cardboard and is filled with incombustible powder which helps to prevent arcing when the fuse blows. In the porcelain-grip fuse the same end may be attained by threading the fuse wire through a tortuous channel. It is generally impossible to fit a new wire to a cartridge fuse, and, by using cases of different dimensions, it can be ensured that only fuses of the intended rating are inserted between a particular pair of terminals. This advantage is shared by the screw plug type of fuse which is essentially a short cartridge fuse arranged to screw into a socket and make contact between two terminals on the same principle as the screw-cap lampholder.

For industrial service porcelain grip fuses are commonly mounted inside a cast-iron case together with switches which are interlocked (§ 373) with the cover of the case so that the cover cannot be opened until the switch is open; neither can the switch be closed whilst the cover is open. The fuses being on the load side of the switch the fuse clips are dead whilst the cover is open and there can be no 'open sparking.' For use in explosive atmospheres the case and its cover are stronger and have wide machined joints to render them 'flame-proof' (§ 366). House-service fuses are of the porcelain grip type mounted, generally without switches, in a small iron case which is sealed to prevent tampering. If the fuses for each pole are in separate cases, the latter should be mounted side by side so as both to open inwards, the distance between the cases being insufficient to allow both cases to be open at once. The fuses for both poles may be mounted in a single casing if provision be made to prevent accidental short circuiting. The cover is often lined with asbestos, and asbestos-covered fuse wire is often employed. Cut-outs of this type are suitable for pressures up to 600 V. Combined switch and fuse units for industrial service can be built for any desired pressure.

An alternative to the explosion-proof air-break switch and fuse

for mining service is the combined oil switch and fuse shown diagrammatically in Fig. 91. The fuse wire, *F*, forms the connecting link between the moving contacts, *A*, *B*, and is always submerged in oil, except when the tank is lowered to allow the fuse to be replaced. The rating of the fuse is, of course, much higher in oil than in air.

Oil-immersed fuses carried by a porcelain cover with hand grip were formerly used on switchboards for high power and high voltage, but it was found that the blowing of the fuse on short circuit was of explosive violence, the fuse tank being often shattered and the oil causing a dangerous fire. Oil-immersed switches with overload trip-gear are therefore now used almost invariably for all high-power circuits and for most circuits above 600 V.

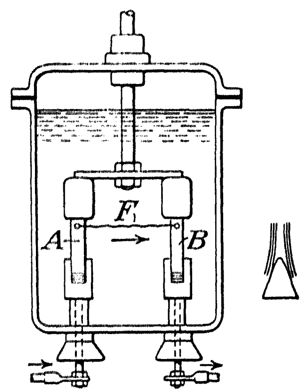


FIG. 91.—Oil-immersed switch and fuse.

The most successful type of high tension fuse consists of a short fuse wire held in tension by a spiral spring, the whole being enclosed in a long glass tube which is filled with carbon tetrachloride. When the fuse blows, the spring contracts and a specially-shaped piston piece attached to it forces the liquid (which is non-inflammable and an insulator) on to the arc. This type of fuse is quite reliable for the protection of potential transformer circuits and of the main circuits of the average industrial consumer taking A.C. supply at, say, 6 600 V; and it is claimed that it can safely be used in generator and other main circuits of 15 000-20 000 kW. at pressures up to 66 000 V.

B.E.S.A. Report No. 88 standardises four sizes of cut-out for use in low-pressure circuits (not exceeding 250 V), the maximum working currents being respectively 10, 30, 60 and 100 A and the corresponding fusing currents 30, 60, 120 and 200 A. 'Ordinary duty,' to which alone these cut-outs are applicable, is taken to mean that the maximum short-circuit current in the circuit cannot exceed 1 000, 2 000, 4 000 or 6 500 A for the respective standard sizes of cut-out (*i.e.* from 100 to 65 times the maximum working currents).

376. Types of Switchboards.—The main types of switchboard to be considered are: (1) The panel type (§ 377), in which the switchgear and instruments for a particular machine, feeder, etc., are mounted on a panel and in an undivided enclosure behind the latter. (2) The cellular type (§ 378), in which each of the main elements of the switchgear for the machine, feeder, etc., is enclosed in a separate compartment behind, or away from, the panel on which the control levers and indicating instruments are mounted. (3) The ironclad and mining types (§ 379), in which ironclad or flameproof switch-gear is assembled on structural steelwork supports, the bus bars, instruments and connections being enclosed like the switchgear; or the whole may be arranged as an ironclad pillar. (4) Draw-out type boards (§ 380) which may be of the ironclad pillar pattern or the panel pattern, the characteristic feature in either case being the disconnection of the gear from the bus bars by the act of drawing it forward on runways. (5) Outdoor assemblies of weather-proof switchgear (§ 381).

377. Panel-Type Switchboards.—There are still in use many low-tension switchboards with the contacts of the switches mounted on the front of slate or marble panels; the stems of the contacts lead through the panel, and nuts at the back hold the contacts to the panel and clamp cable lugs, etc., to the contact stems. On the front of the panels are open-type knife switches, field-regulating rheostats, etc.; also, the measuring instruments and, at the top of the panels (so that the arcs have a clear path upwards), the air-break circuit breakers. Even where none but skilled attendance is provided such open-type panels are dangerous for any higher pressure than 250 / 500 V, 3-wire, D.C., and the trend of modern design is to place nothing but the control handles and indicating instruments on the fronts of panels, all the live parts being protected from accidental contact.

Early high-voltage switchboards were often of the open type with both switches and connections on the front of the panels, the risk of accidental contact, short-circuit, and flash-over being reduced by placing barriers of slate between the components at right angles to the panels. The modern cellular switchboard (§ 378) is a development of this principle.

There is little advantage in using slate or marble panels for any but low-voltage boards. Apparatus for pressures exceeding 650 V is usually insulated by porcelain and carried by steel or cast-

iron supports on a rolled steel framework. A typical panel-type board for high-voltage circuits comprises a framework of channel and angle irons with sheet-steel front panels. An enclosure is made behind each panel by sheet steel or expanded metal partitions and a door at the back gives access to each cubicle from a gangway between the 'board' and the wall. The control levers project through the front panel, and the latter carries the indicating instruments. When the doors are closed all the live parts are completely inaccessible, and the doors may be interlocked with isolating switches so that the gear in the cubicle cannot be live whilst the door is open (unless it is deliberately made live for purposes of testing). The whole of the metal framework, panelling, etc., is bonded together and connected permanently to earth.

378. **Cellular Type Switchboards.**—In these boards, metal or insulating sheets, or brickwork or concrete partitions, are placed between panels and, to a greater or less degree, between the component parts of the equipment on each panel. The aim is to establish mechanical barriers (insulating or of earthed metal) between phases and, as far as possible, between individual pieces of apparatus. The trend of modern construction is towards the use of concrete walls and partitions in conjunction with a structural steel framework. The latter is arranged so that there is a minimum of earthed metal in the cubicles of the board and so that doors and other fittings can be mounted by the maker of the board without demanding special accuracy in the erection of the concrete or moulded stone slabs at the site. Concrete or moulded stone is more convenient to use and more compact than brickwork, and it withstands arcing or explosions better than steel or thin sheets of insulating composition; also it can be moulded with holes, seatings, etc., for attachments. Thoroughfare insulators are used to carry connections through the concrete partitions in the cubicle structure.

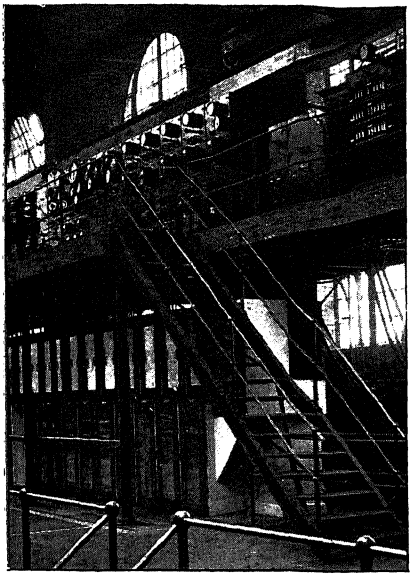
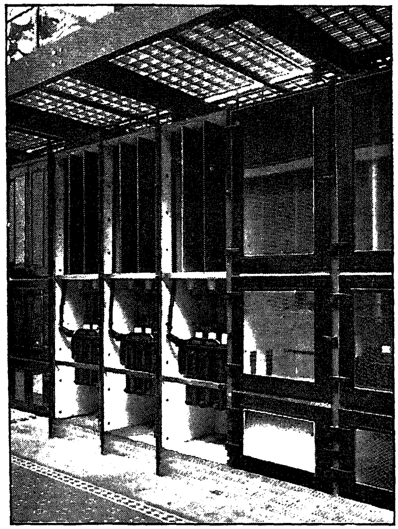
A concrete or similar partition gives the same operating safety as a much greater air gap between live parts and this favours compact construction. On the other hand, the minimum permissible clearance to earth must be allowed between partitions and the gear enclosed and every partition must be at least 2 ins. thick; also, for practical reasons, the cells must be rectangular and of uniform depth, so that too much space is occupied if the cellular principle be carried too far. More compact construction is possible if doors

can be provided in both the back and the front of the board. The bus bars may be mounted in concrete troughs along the top of the board or, where duplicate bus bars are used, at the back and front of the top compartment in the board. The isolating links occupy a cell immediately below the bus bars. The oil switch stands on the floor, and behind it (in separate cells, if access can be had to the back as well as the front of the board) may be the instrument transformers and the protective transformer. There are many other possible arrangements. The vent pipe from the oil switch discharges outside the cubicle.

Switchgear in this type of board is generally 'remote-controlled'—either mechanically or electrically from a control desk on which also are mounted all the indicating, recording, and synchronising instruments, etc. The construction is costly if the subdivision be thorough and of substantial construction, and if the individual cells be large enough for convenience in access. On the other hand, the strong walls and partitions are valuable from the mechanical standpoint in that they afford substantial supports for the gear; and the barriers undoubtedly reduce the risk of accidental short circuiting by tools, etc., and prevent the spreading of damage by fire or flash-over.

379. Ironclad and Flameproof Switchboards.—The switchboards described under this heading are particularly useful for general industrial service. They are compact and simple, and all the components are protected against mechanical injury and against accidental contact with live parts. For low and medium voltage circuits, in situations where the atmosphere is not explosive, the board may be built up from ironclad air-break switches, ironclad fuses, and ironclad instruments mounted on a supporting framework of angle irons or steel tubing. Connections between the ironclad components may be by insulated conductors enclosed in steel conduit, or the casings of the components may be designed so that they can be bolted together directly; with the latter arrangement the various components can be supported by a cast-iron pedestal or pillar instead of a framework of tubing or rolled sections. Whichever of these arrangements be employed, the casings and the supporting structure—in fact all exposed metal—is permanently earthed.

The unit method of construction of ironclad switchboards is by no means limited to simple distributing boards. Thus Fig. 92 shows the connections of the

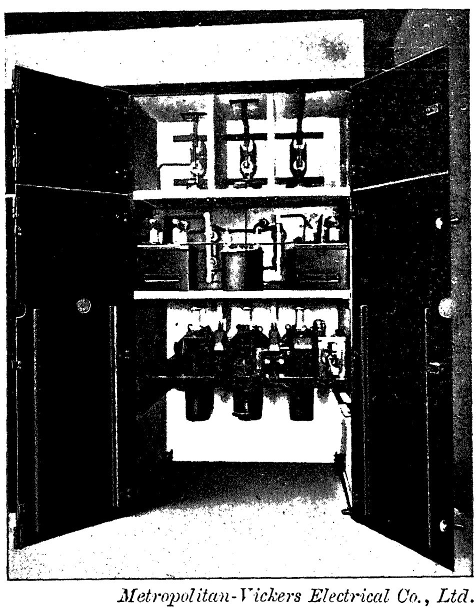
Ferguson, Pailin, Ltd.

CONTROL BOARD AND E.H.T. CELLS WITH MECHANICAL REMOTE-CONTROL.

The cells are of moulded stone having steel doors provided with reinforced glass windows. The oil-immersed circuit breakers have a rated rupturing capacity of 250 000 kVA. A separate welded-steel elliptical tank is provided for each pole and is fitted with a treated wood lining. The generator breakers are provided with a half-cock synchronising position. Remote control is effected by a special system of levers with pipe drive.

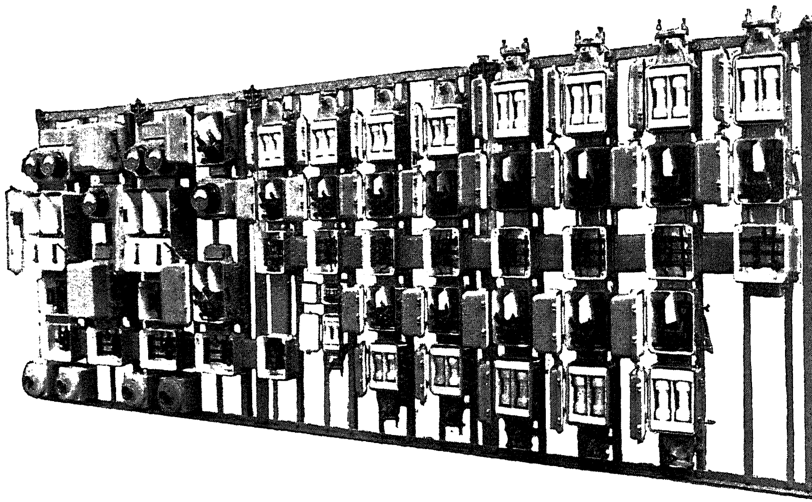
STONEWORK CUBICLE-TYPE SWITCHBOARD.

The cubicle is built up of moulded stone slabs cemented into a wrought-iron framework; the latter takes all shocks and stresses of operation. The illustration shows the oil circuit breaker with its closing contactor, the oil-immersed potential transformers with primary fuses, and the isolating switches for one set of bus bars. Similar cubicles, on the other side of the central wall, accommodate the isolators for the second set of bus bars, the current transformers, and (for ring mains) the isolators on the feeder side of the oil circuit breaker. The bus bars are in moulded stone troughs along the top of the cubicle, and the steel doors for the isolator compartments are separate from the main doors. The circuit breaker vent pipes are not in position in the illustration, and the phase barriers between the potential transformers have been removed to make way for a special transformer, but the grooves for them can be seen.



Metropolitan-Vickers Electrical Co., Ltd.

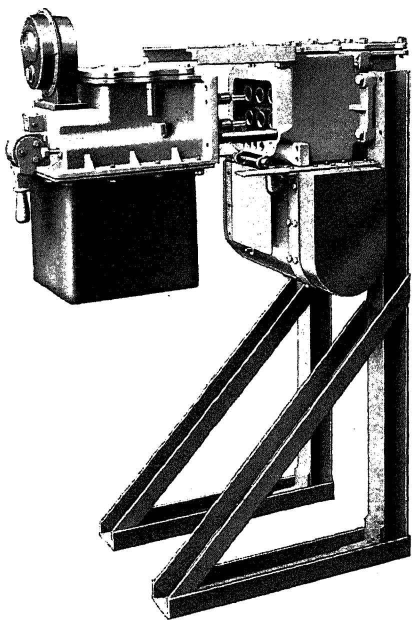
[*To face p.* 548.



Mavor & Coulson, Ltd.

IRONCLAD SWITCHBOARD BUILT ON THE UNIT PRINCIPLE.

The board illustrated includes all the switchgear necessary for the control of two pairs of 3-wire generators and fourteen feeders (*see also* Fig. 92). It is built in four sections for easy handling and shipping. Similar assemblies, with flameproof gear throughout, are supplied for use in fiery mines or other situations where the atmosphere is explosive.



British Thomson-Houston Co., Ltd.

TOTALLY-ENCLOSED SWITCHGEAR OF UNIT CONSTRUCTION.

This type of switchgear is equally suitable for mining service or for industrial service indoors or outdoors. It can be mounted on wall or pedestal, and can be used with draw-out or non-drawout circuit breaker. In the draw-out pattern illustrated, the shrouded sockets render accidental contact impossible, and the safety interlocks eliminate all risk of 'open sparking.' Cable boxes or conduit fittings can be attached to the top, bottom, or back of the connection chamber (behind the socket chamber), and the bus bar chambers (below the sockets) can be bolted together to form a continuous chamber for a complete switchboard.

[*To face p.* 549.

board illustrated opposite for the control of two pairs of 400 / 200 V, 3-wire, D.C. generators, ten 400 V feeders, and four 200 V feeders. Each pair of generators is controlled by a double-pole overload and reverse-current circuit breaker and a double-pole switch. Double-pole equalising switches are also provided for equalising the series windings of the generators. Each generator has its own moving coil ammeter, and a voltmeter with voltmeter switch is provided for each pair of generators. Four shunt regulators, one for each generator, are mounted at the bottom of the generator panels. Each of the outgoing feeder panels consists of a double-pole ironclad switch with double-pole fuse box. The 400 V feeders are connected between the two outer bus bars, and the 200 V feeders are connected between outer bar and inner, and balanced. The cable fittings for the feeder panels are all suitable for two-core, wire-armoured cable, those for the generator connections being arranged for V.I.R. cable. Each pair of generators is driven by an A.C motor mounted between them, the switchgear for the motors being separate from the D.C. switchboard.

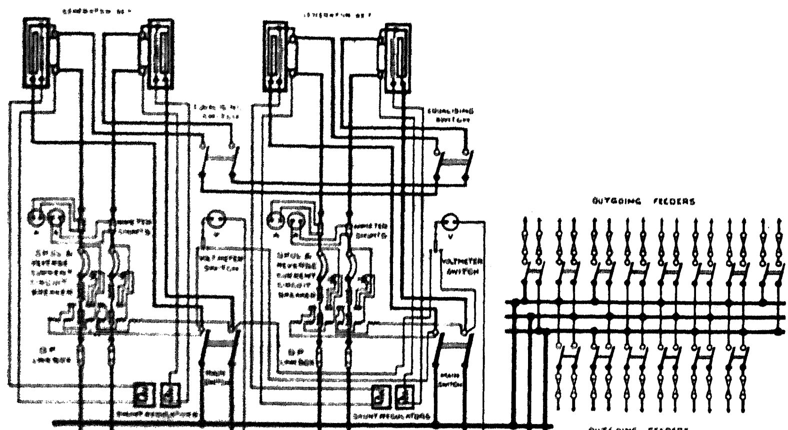


FIG. 92.—Connections of switchboard for the control of 3-wire generators and feeders (*see also* Plate opposite).

For mining service the switchgear must be flameproof (§ 366) and there is a tendency to employ standard 'mining-type' switchboards for other industrial services where the atmosphere may be more or less explosive or where rough usage, moisture, etc., may be expected. In such cases, and for any pressure higher than 600 V (whether the atmosphere be explosive or not), it is usual to employ oil switches.

Whether the gear be flameproof or simply 'ironclad,' and whether air-break or oil-immersed switches be used, the general arrangement is the same. The casings of the components, together with the conduit (if any) between components, form an earthed metallic enclosure for the live parts and connections. The covers

are interlocked so that no live parts can be inadvertently exposed. Cables are led in through watertight glands, conduit fittings, or sealing boxes filled with insulating compound, as the case may be. In the case of assemblies representing several 'panels,' the components of each panel and the panels themselves are built together on the unit principle. The bus bars which run through the group of 'panels' are encased like the rest of the gear; they may be bare and mounted on porcelain insulators, or micarta-sheathed and carried by insulating bushings, or bare rods supported by bridge-pieces may be 'run solid' with insulating compound. Any measuring instruments required may be mounted beneath cast-iron covers with reinforced glass windows; automatic releases are similarly protected. There is no limit to the number and variety of components which can be assembled to provide a switchboard for any desired purpose.

380. **Draw-out Switchboards.**—The draw-out type of switchboard originated by the firm of Reyrolle is now made in a number of patterns, the essential feature being that the whole of the switchgear is mounted on some form of carriage and is entirely isolated (*i.e.* 'dead') when the carriage is drawn out on its runway. This is accomplished by plug or knife contacts on the removable portion of the gear which engage with fixed bus bar and feeder contacts only when the carriage is in its service position, all the live parts being then inaccessible to the operator, and the various covers of the gear and the oil-switch tank being incapable of removal. If it is desired to inspect or adjust any of the live parts, or to open a cover or lower the oil tank, the switch must first be put into the 'off' position. The carriage can then be drawn out by a handle or racking gear provided for the purpose. Directly the contact plugs on the moving portion leave the fixed contact sockets (which they do before either becomes accessible to the operator) shutters fall automatically in front of the fixed contacts. When the carriage is withdrawn to the limit of its travel, all the components which it carries are completely accessible and entirely disconnected from the circuit contacts; at the same time, the circuit contacts are covered by shutters. The plug and socket contacts act as isolating switches on both sides of the gear on the carriage; they are separated automatically by the act of drawing out the carriage and, in order to ensure that these contacts are not used even inadvertently to make or break a current (§ 362), it is arranged that the carriage can be

neither withdrawn nor returned unless its main switch is 'off.' The carriage runs on a machined track in order that the plug contacts may keep in alignment with their sockets.

'Armoured' draw-out switchboards resemble the mining-type boards described in § 379 as regards the mechanical nature of their 'ironclad' protection but in the draw-out boards of this type a fixed panel contains the incoming and outgoing leads (*e.g.* bus bars and feeders) and the contact sockets of each, whilst the oil switch, automatic trip gear, ammeter, voltmeter, etc., are mounted on a carriage. The carriage runs on substantial knee-brackets fixed to each side of the back panel. As many panels as may be required can be assembled side by side on the unit principle. Armoured panels of this type are used in all sizes from those suitable for individual motors in mining service to those capable of acting as circuit-breaker panels in large central stations. As the whole of the gear is totally enclosed, and proof against weather and vermin, it can be used out of doors.

'Truck-type' or 'panel-type' draw-out switchboards resemble ordinary panel-type high-voltage boards (§ 377). The incoming and outgoing bars and cables with appropriate contact sockets are mounted at the back of the enclosure behind an earthed metal screen with automatic shutters for the apertures through which the contact plugs normally pass. The whole of the rest of the gear and the front panel itself are carried by a framework, which has rollers and runs on an accurately machined track. No gangway is needed behind the enclosure or between panels for access; the whole of the gear can be wheeled clear of the board for inspection or overhaul and a spare panel can be run into the empty cubicle to maintain service if necessary.* This type of draw-out board is lighter in construction than the armoured type described above and it is not weatherproof but it is entirely satisfactory for indoor applications, with currents up to, say, 500 A per panel at 11 000 V. The armoured gear is built with 3-phase circuit breakers capable of carrying, say, 400 A at 44 000 V or 1500 A at 22 000 V, and of 500 000 kVA breaking capacity (§ 371); with single-phase circuit breakers (*i.e.* three coupled circuit breakers in separate tanks for a 3-phase circuit) much higher breaking capacities can be obtained.

* This advantage, which is enjoyed also by 'armoured' draw-out gear, is attained only in draw-out boards and is of great practical importance.

381. Outdoor Switchgear.—Outdoor substations, comprising transformers and switchgear, have been used in America for many years past and there is no doubt that this practice will extend as extra high-voltage transmission becomes more common. The obvious advantage is the great saving on cost of buildings, simple concrete foundations and light structural steelwork supports being used instead of a masonry structure and its heavier foundations. The obvious difficulty is the exposure to weather. As stated in § 380 armoured draw-out switchgear is completely weatherproof and ordinary high-voltage circuit breakers are quite reliable for outdoor service if fitted with suitable terminal bushings and if the closing and trip gear be protected by a weatherproof casing. Similar remarks apply to high-voltage static transformers. The switchgear and transformers are, in fact, at least as reliable as the transmission lines so far as atmospheric conditions are concerned; if severe cold is experienced the oil can be kept at any desired temperature by aid of thermostats and electric heating coils. The large air gaps between lines and the long terminal bushings required at extra high pressures, together with the large dimensions of e.h.t. switchgear and transformers, combine to make masonry switch houses large and costly. With outdoor gear the clearances must be increased to allow for swinging of conductors and the possibility of birds perching on or flying between live parts. At pressures below 25 000 V outdoor switchgear is probably more costly than indoor gear (including the structural work in both cases), but at 50 000 V there is a saving of 25-30 % in the total cost of an outdoor equipment,* and the saving is still greater at higher pressures.

382. General Arrangement and Construction of Switchboards.—Much information on this subject is embodied in the preceding paragraphs, to which the following excerpts and summaries may be added.

The I.E.E. Wiring Rules, Nos. 87-93, deal with the position, construction, and arrangement of switch and distribution boards:—

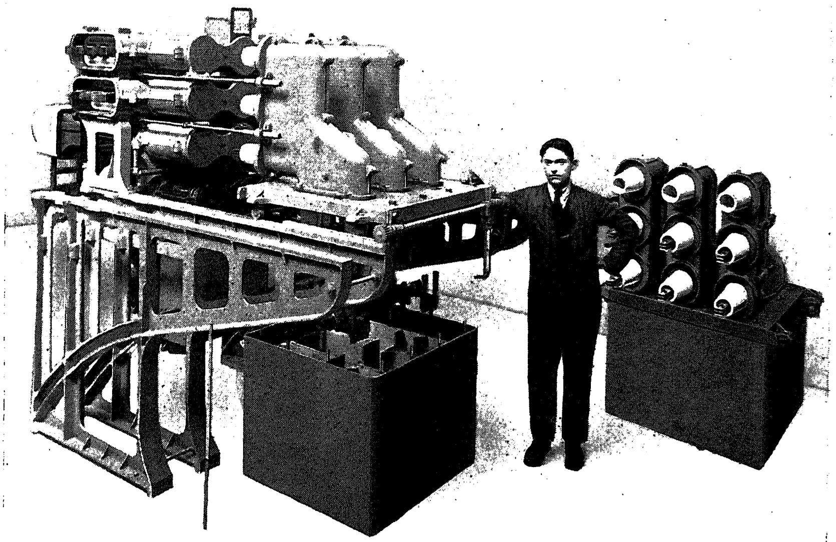
87. *Position; Construction.*—Main and distribution switch and fuse boards may be used under the following conditions:—

(*a*) They must be—

(i) Fixed in dry situations;

---

* According to an article by J. B. Rudkin, *El. Rev.*, Vol. 90, p. 567, describing outdoor switchgear at Goesgen (Switzerland) for 135 000 V.

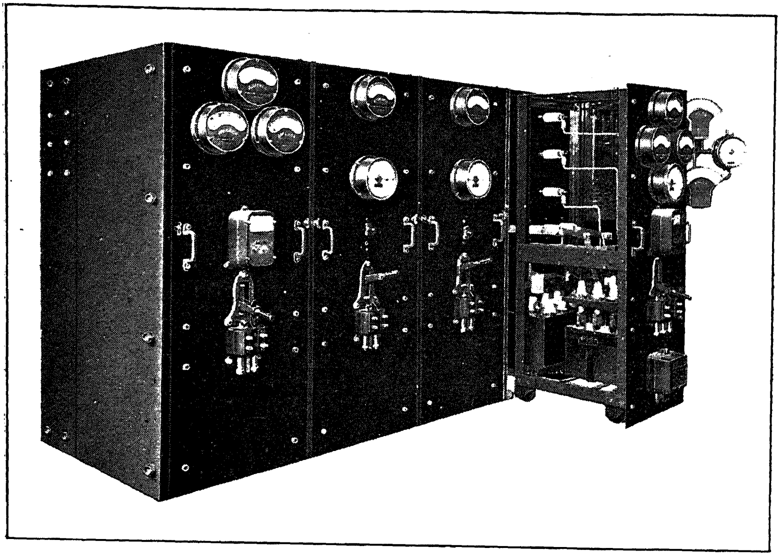


A. Reyrolle & Co., Ltd.

ARMOURED DRAW-OUT SWITCH FOR 12 000 V, 3-PHASE, 750 A.

This switch is suitable for controlling generating plant in a station having an aggregate capacity of 50 000 kW. The equipment comprises two sets of 3-phase bus bars, a 3-phase oil-break switch, three current transformers, 3-phase potential transformers (mounted on a carriage behind the switch), and cable dividing boxes. Every conductor is 'ironclad;' and the bus bars, current transformers, etc., are immersed in insulating compound. When the switch carriage is withdrawn (as shown) for access to the working parts, the live portions are screened by shutters which fall across the socket openings. (Note the yard rule against the standard in the foreground.)

[*To face p.* 552.



Johnson & Phillips, Ltd.

DRAW-OUT TRUCK TYPE SWITCHBOARD.

The stationary portion of each cubicle is bolted to the floor and contains the bus bars, fixed contacts, cable box, or cable sealing end. The truck carries the oil switch, current, and potential transformers, and the instruments which are mounted on the front plate. When the truck is withdrawn for inspection all the parts upon it are automatically rendered 'dead' and, at the same time, the fixed contacts, which remain 'live,' are automatically screened.

[*To face p.* 553.

(ii) So arranged that a fire thereon cannot spread, whether occurring at the front or back;

(*b*) Their bases must be of incombustible and insulating material, and fitted with moisture-proof bushes at the points of support if the material is hygroscopic;

(*c*) The possibility of a permanent arc must be prevented either by sufficient spacing of all live parts, or by the use of separating partitions.

88. *Accessibility.*—Switch and fuse boards must be so constructed and placed that all their parts which may have to be adjusted or handled are readily accessible.

89. *Connections.*—Connecting conductors on main boards must be—

(*a*) Permanently accessible from either the back or the front of the board;

(*b*) Symmetrically placed and spaced apart;

(*c*) So proportioned that there shall be no appreciable rise of temperature when the current flows through them;

(*d*) So arranged that the course of every conductor may, where necessary, be readily traced;

(*e*) So arranged as to prevent the access of acid fumes from batteries to the board.

90. *Labels.*—Switchboard circuits should preferably be labelled for identification.

91. *Open-type Fuses.*—No open-type fuses may be placed at the back of switchboards.

92. *Metal Cases.*—The cases of instruments, if metallic, must be insulated from the circuits, but they may be earthed if desired.

93. *Fuses.*—Every voltmeter or pilot lamp with its connecting wires should be protected by a fuse on each pole.

Some of the factors to which attention is called in connection with mines (Chapter 32) are of general application; and the following points, from a Memorandum (1916) of the British Home Office, may also be noted:—

It is undesirable that main fuses should be placed behind the panels of low or medium pressure switchboards. The blowing of a fuse, particularly under heavy short-circuit conditions, on a station switchboard, might readily lead to a further short circuit. If fuses for instruments, etc., are placed behind switchboards they should be guarded so that an arc cannot spread, and placed so as to be accessible. In the case of large switchboards there should be access to the back from both ends, to obviate an attendant being trapped in case of accident. For screening off high-tension boards expanded metal is recommended. On polyphase boards there should be divisions or barriers between phases at all places where an arc is liable to be accidentally started, *e.g.* at isolating switches, etc. On high-pressure boards, isolating switches should be placed on both sides of oil-switches on feeder circuits where the feeders are capable of being made live from the distant end.

Other points, many of which are embodied in the preceding paragraphs of this chapter, are as follows:—

Separate panels for each machine, transformer, feeder, etc., make for safety and simplicity in operation and maintenance. In many existing stations the high voltage and low-voltage panels are on different floors. It is generally most convenient to place the main oil switches and transformers on the ground floor or in

the basement; with remote electrical control the control gear can be placed wherever convenient; remote mechanical control is less flexible in this respect. Remote electrical control, placing all the main switches of the station under the direction of one man, is almost standard practice in large new stations; where there are inter-connected stations a 'load dispatcher' may control the men on the master switchboards of the individual stations by telephone.

On boards for direct manual operation fuses should be enclosed and away from face level. Air-break circuit breakers and lightning arresters should always have a clear path upwards for arcing. Instruments should always be where they can be read easily and without parallax from the operator's station; also, they should be away from rheostats or other sources of heat. On control desks for remote electrical control ammeters, voltmeters, and synchroscopes should be in full view at the back of the desk; switch levers or buttons, rheostats, and synchronising plugs should be easily accessible; relays, integrating watt-hour meters, and other equipment to which only occasional reference is required may be at the bottom of the panel.

All main current-carrying conductors should have good facilities for cooling and be free to expand and contract without serious restraint. Iron should not be placed where it would be subject to stray fields. All parts in which eddy currents may be induced should be non-magnetic and of high electrical resistance (natural or produced by saw cuts or other device).

Conductors, fuses, contacts, and other current-carrying parts should be inaccessible whilst they are 'live,' and all exposed metal work should be earthed. Provision should be made to prevent unauthorised operation of switchgear or access to live parts, and means should be provided for the definite locking of switches 'off' in case of need. Interlocking to ensure correct sequence of switching and to prevent access to live parts should be employed wherever practicable. The general design and arrangement of switchgear should facilitate cleaning and supervision, and it should be possible to get complete and easy access to all parts for repair (subject to the parts being first rendered 'dead').

383. Bus Bars and Switchboard Connections.—In all but small installations the bus bars are in duplicate and provision is made for sectionalising them. The bar for each pole or phase may be (electrically) in the form of a closed loop or 'ring main' with isolating switches at intervals so that any desired section can be isolated for cleaning or repair. Alternatively two sets of bars may be used with isolating switches in each and with cross-connecting switches, so that any desired section of one set of bars can be isolated and replaced by a section of the other set. The insertion of reactance coils between the sections of bus bars fed by different generators limits the power flowing to a short circuit (§§ 340, 370).

Bus bars generally consist of a number of relatively thin strips, of copper or aluminium. The width of the strips may be, say, 8-12 times their thickness, and the strips are mounted on porcelain or other insulators with their width in a vertical plane, thus securing maximum stiffness against deflection by their own weight.

The strips composing each bar are electrically in parallel, but should be held definitely apart by spacing pieces. The object of the laminated construction is to reduce eddy currents and increase the radiating surface.* Extra strips can be added at any time if the carrying capacity of the bars has to be increased. The strips for each bar are side by side in a horizontal plane, but the bars themselves may be in either a vertical or a horizontal plane. Placing the bars in a horizontal plane reduces the overall height of the board, but it must be possible to get at the bars from above for cleaning. Bars in a vertical plane are more easily accessible as a rule, and their maximum stiffness is then opposed to the mechanical forces developed between the bars on short circuit.

Aluminium offers important advantages as a material for bus bars. The larger cross-section required for the same electrical conductivity makes aluminium compare unfavourably with copper where insulated cables are concerned, but in the case of bus bars the difference in dimensions between copper and aluminium is of no appreciable importance as regards the cost of the insulating supports. On the other hand, the larger radiating surface of the aluminium bars, and the fact that their weight is roughly half that of the equivalent copper bars, are important advantages. Adhering to commercial sizes of bar or rod it will be found that aluminium bars of the same width, but 50 °/₀ thicker than the copper bars which would be used, or aluminium rod 1¼ times the diameter of copper rod, gives sufficiently nearly equal conductivity. The exact value of the resistance of bus bars is unimportant, since it is always very low. On the other hand, care is required to avoid high local resistance at joints.

The best method of connecting consecutive lengths of aluminium bar is by overlapping the bars for a distance equal to 10 or 12 times their thickness and bolting them together. The contact surfaces should be coated with vaseline and then rough filled, the file cuts being at right angles on the two surfaces; the surfaces are then clamped together *without removing the dirty*

---

*It is the radiating surface which determines the permissible current density for given temperature rise. A 2 in. × 1 in. copper bar carrying 2 000 A has 0·036 sq. in. of radiating surface per ft. run per amp., compared with 0·018 sq. in. in the case of a 4 in. × 2 in. bar carrying 8 000 A. If the larger bar be divided into eight strips each 4 in. × ¼ in., spaced well apart, the radiating surface is increased to 0·102 sq. in. per ft. run per amp.

*vaseline.** Joints made in the same way between copper bars have as low resistance as soldered joints. Permanent connections between copper or brass parts are often tinned and 'sweated,' but any sweated joint should be supplemented by a grub screw, bolt, or other mechanical device. The advantage of tinning the surfaces of copper joints which are to be clamped lies in the fact that the soft tin spreads and gives contact over a greater area; also, the flow of the metal during the final stages of clamping exposes clean surfaces at the contact. The use of tinfoil in clamped joints does not reduce, but generally increases, the contact resistance.

Aluminium bus bars are practically immune from corrosion (even in battery rooms), but joints between aluminium and other metals should be painted to exclude moisture; otherwise electrolytic corrosion will occur. Similarly, where aluminium rests upon plain slate, or other material capable of carrying a leakage current when damp, the aluminium should be painted or a piece of mica should be placed between the surfaces.

Most of the high voltage connections on modern switchboards consist of bare copper strip or rod, thus reducing the amount of inflammable material in the construction. Rod can be bent equally easily in any plane, but rectangular strip is difficult to bend in the plane of its width. All connections must be so supported that they cannot be deformed to any dangerous degree under short circuit conditions (§ 338); at the same time, bus bars and all strip or rod connections must have lateral freedom or sufficient flexibility at bends to allow for thermal expansion and contraction. Varnished cambric offers advantages as an insulating material for switchboard cables (§ 287).

Low voltage connections in instrument and relay circuits, etc., are commonly made by V.I.R. wires (preferably with fire-resisting braiding), supported on porcelain cleats. It is convenient to have the circuits arranged so that standard instruments can be connected quickly for calibration tests.

384. **Instrument Transformers.**—The function and general characteristics of current and potential transformers are discussed

* Any attempt to remove the dirty vaseline exposes the clean filed metal to oxidation; the whole object of the method of preparation described is to protect the clean metal from even momentary exposure to the air. Joints made as described do not deteriorate during a period of years (*vide El. Times*, July 27, 1911, p. 77; and *Jour. I.E.E.*, Vol. 60, p. 889).

in § 108. Ring-type current transformers threaded on the terminal leads inside the oil-switch casing are convenient for the operation of ammeters, overload trips, or other devices unaffected by phase error in the transformer (*see* § 108), but they should not be used for any device operating on the wattmeter principle or demanding special accuracy and uniformity of calibration. In transformers provided with a primary winding the carrying capacity of the latter should be equal to that of the main in which the transformer is connected.

It is important that the resistance in the secondary circuit of current transformers should be as low as possible; an ammeter and a trip coil can be operated in series in this circuit if the trip gear is sensitive (*i.e.* does not require much power for its operation), but the current element of any wattmeter type device should not be in series with a trip coil because the phase error caused by the latter would lead to serious inaccuracy. The same current transformer can generally be used to serve an ammeter, wattmeter, and core-balance protective gear, but the maker's advice should always be taken in regard to the loading of instrument transformers. In mining or armoured switchgear (§§ 379, 380) the use of current transformers can often be avoided by mounting the ammeter inside the switch case and connecting it in the h.t. circuit (with its case at line potential): suitable clearance is provided between the instrument and the earthed case of the switch, and the instrument is read through a window.

Potential transformers for pressures up to 6 600 V are generally air-cooled, those for higher pressures being oil-immersed or enclosed in a casing filled with insulating wax or compound; cases filled with wax or compound should be mounted so that the filling cannot escape if it softens or melts in service. Any number of instruments, etc., can be connected in parallel to one potential transformer provided that the rated output of the latter is not exceeded (§ 108). Voltmeters, low-voltage releases, and synchroscopes in a 3-phase system can be used in conjunction with a potential transformer on one phase only, but potential transformers are required on at least two phases for wattmeters and reverse-power relays (§ 110).

Instrument transformers for use in automatic selective protection systems have generally to fulfil special conditions in regard to their characteristics (§ 359).

385. Equipment of Typical Switchboards.— and conditions of service of switchboards differ so useful purpose would here be served by detailed individual boards; for this the reader must be r technical press and the proceedings of profession The following notes on the usual equipment of v panels (according to whether the supply is A.C. or I ever, be useful:—

Generator Panel.—The generator leads are connected (switches if required) to circuit breakers whence connection isolating switches in the case of high-voltage machines) to tl station. Voltmeter, frequency meter, and synchroscope conn made on the generator side of the main switch or circuit breaker ammeter (or ammeters in the case of a polyphase machine) is als generator side of the main switch.* It is desirable that watt-hour on each generator panel. A field-regulating rheostat and amme addition to a field switch with auxiliary contacts which close the safe discharge of the energy stored in the field. Over-load or other protective relays are required, and a power factor ind Synchroscopes may be placed on a bracket projecting from one e or machine and bus bar voltmeters together with the synchro located on a special synchronising panel.

Balancer Panel.—There are many systems of balancing 3- each of which requires appropriate switchgear. With the s equipment (two auxiliary machines in series between the 'oute required on the control panel is three single-pole switches, tw rheostats, and an ammeter in each machine circuit.

Summation Panel.—This panel (for measurements only) meter recording the total output of a number of generators, quency meter and a power factor indicator.

Control Panel.—The equipment comprises master switches the low-voltage D.C. circuits of the coils or servo-motors operatin switchgear; also, the measuring instruments of the main circu these instruments being served by instrument transformers on t

Battery Panel.—There are many possible arrangements of s their auxiliaries to suit various applications and different meth the change in voltage per cell during charge and discharge (C

Where end-cells are used for regulation the battery panel ca lating switch so that the number of cells across the bus bars and can be varied independently. There are also an ammeter an between the battery and the bus bars. The same or an adjoini generator switch (with minimum cut-out) fuses, ammeter, fiel change-over switch by means of which the generator can b

---

* It is usual to connect all the instruments, on the gene gene ator side of the main circuit breaker. This ensures that a are dead when the bieaker is open and the generator is static transformers are always placed on the generator side of the circ

battery or to the bus bars as desired. By means of a 3-way switch a single voltmeter can be used to measure the generator, bus bar, and battery voltages.

If a reversible booster set be used to add to the voltage of the main generator during charging, or to that of the battery during discharging, no 'end cells' are needed for regulation. The battery circuit includes an ammeter and fuses, and a double-pole change-over switch by means of which the cells can be connected straight to the bus bars or in series with the booster. The motor driving the booster requires an ammeter, double-pole switch, fuse and starter; whilst the booster requires a field reversing and regulating switch and a circuit breaker which opens if the fuse blows in the booster-motor circuit. Two voltmeters with multi-way switches provide for measuring the generator, bus bar, booster, and battery voltages.

Station Panel.—The equipment on this panel provides for the control of the station lighting and auxiliary power circuits. Change-over switches are required if (as is desirable) there are alternative sources of supply. Main switches, starters, rheostats, measuring instruments, etc., are provided for the individual circuits supplied, according to requirements. (See also *Distribution and Motor Panels.*)

Feeder Panel.—On station feeder panels connections are taken from the bus bars through an air-break or oil-immersed circuit breaker to the outgoing cable. A voltmeter on the bus bar side of the circuit breaker shows the bus bar voltage, and an ammeter between the circuit breaker and the feeder shows the load on the latter. If desired an integrating watt-hour meter may be fitted to measure the energy supplied; a recording ammeter or wattmeter is sometimes useful. Overload and split conductor or other protective relays (§ 359) are required on each feeder panel. One frequency meter may serve a number of feeder panels.

Distribution Panel.—The incoming mains are connected through a switch or circuit breaker, as the conditions may demand, to the distribution bus bars. To the latter the load circuits are connected through knife switches or oil switches with fuses in either case, or through circuit breakers if required. Small distribution boards as used for house-lighting circuits are described in Chapter 22. The consumer's panel in an industrial installation taking energy at high voltage requires an oil-immersed circuit breaker with isolating switches on the line side, and instrument transformers if the energy be metered on the line side of the step-down transformer. The low-voltage terminals of the main transformer are connected to a distribution panel which has a voltmeter and main ammeter and, if desired, ammeters and energy meters for the individual circuits supplied from the distribution bus bars. Where the supply tariff takes account of power factor, it is advisable to provide a power factor indicator or recorder for the installation as a whole or, if practicable, for each of the main circuits.

Motor Panel.—The incoming mains are taken to a main switch (double- or three-pole) of the type appropriate to the electrical and service conditions. Thence leads are connected through fuses to the starter (Chapter 29). The provision of an ammeter on each motor panel contributes greatly to safety in operation and efficiency in maintenance. It is useful to arrange for the easy connection of a recording wattmeter in the motor circuit at any time for the purpose of a power test.

General.—Isolating switches should be provided on all high-voltage panels so that the whole of the gear can be disconnected from the incoming and outgoing leads; with draw-out gear no special isolating switches are required. Instrument transformers are generally required on heavy current and / or high-voltage A.C. panels (§§ 108, 384).

Where automatic protective gear is used the appropriate transformers, relays,

etc., are mounted on the switchboard (§ 359). If fuses are used they are inserted in each pole or phase of the circuit, but overload relays need be connected only in one side of each possible lead and return path (*i.e.* one relay for a D.C. or single-phase 2-wire circuit; two relays for a D.C. 3-wire, two-phase 4-wire, or three-phase 3-wire circuit; and three-relays for a three-phase 4-wire circuit. Where reverse power relays are used they should be fitted to each generator and to each one of a group of feeders working in parallel.

Voltmeters and ammeters should be used in each phase of a polyphase system if the load may be unbalanced. Recording instruments are provided wherever a permanent, continuous record is required. Where attention is paid to power factor correction, power factor indicators should be fitted on generator, converter, and feeder panels. Air- or oil-temperature indicators, water- or oil-flow indicators, and other special devices may be mounted on the appropriate main panel, or on the control panel if remote control is practised. Remote electrical control can be provided on any panel. Lightning arresters are desirable on any panel which is connected to overhead lines.

386. Bibliography (*see* explanatory note, § 58).

REGULATIONS.

H.O. Electricity Regulations for Factories and Workshops.

H.O. Regulations as to the Installation and Use of Electricity in Mines.

I.E.E. Wiring Rules.

STANDARDISATION REPORTS, ETC.

(1) *B.E.S.A. Reports.*

No. 109. Specification for Air-Break Knife Switches and Laminated Brush Switches for Pressures not Exceeding 660 V.

No. 110. Specification for Air-Break Circuit Breakers for Pressures not Exceeding 660 V.

No. 116. Specification for Oil-Immersed Switches and Circuit Breakers for Alternating Current Circuits.

No. 124. Specification for Totally Enclosed Air-Break Switches for Pressures not Exceeding 660 V.

No. 126. Specification for Flameproof Air-Break Switches for Pressures not Exceeding 660 V.

No. 127. Specification for Flameproof Air-Break Circuit Breakers for Pressures not Exceeding 660 V.

No. 130. Specification for Totally Enclosed Air-Break Circuit Breakers for Pressures not Exceeding 660 V.

(*See also* B.E.S.A. Reports on Motor Starters and Controllers, Chapter 29, Bibliography).

(2) B.E.A.M.A. Standardisation Rules for Electrical Machinery.

BOOKS.

Electric Switch and Controlling Gear. C. C. Garrard (Benn Bros.).

High-Tension Switchgear. H. E. Poole (Pitman).

High-Tension Switchboards. H. E. Poole (Pitman).

I.E.E. PAPERS.

Switchgear Standardisation. C. C. Garrard. Vol. 56, p. 213.

Note.—Much information on switches and switchgear is contained in papers which deal primarily with other subjects.

MISCELLANEOUS.

Important articles appear frequently in the technical press. *See also* the Bibliographies of Chapter 15 (§ 360) and Chapter 29 (Vol. 2).

INDEX TO VOLUME I.

E

nserted in
y in one
ase
e

ELECTRICAL ENGINEERING PRACTICE.

CONTENTS OF VOLUME II.

PART IV.

Transformation, Conversion, and Storage.

PART V.

Distribution and Control in Branch Circuits.

PART VI.

Applications of Electrical Energy.

PART VII.

Specifications: Testing: Rules and Regulations.

INDEX TO VOLUME I.

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

INDEX TO VOLUME I

References are to numbered paragraphs, not to pages.

References are to numbered paragraphs, not to pages.

PRINTED IN GREAT BRITAIN BY THE ABERDEEN UNIVERSITY PRESS, ABERDEEN